THE EARTH AND ITS HISTORY

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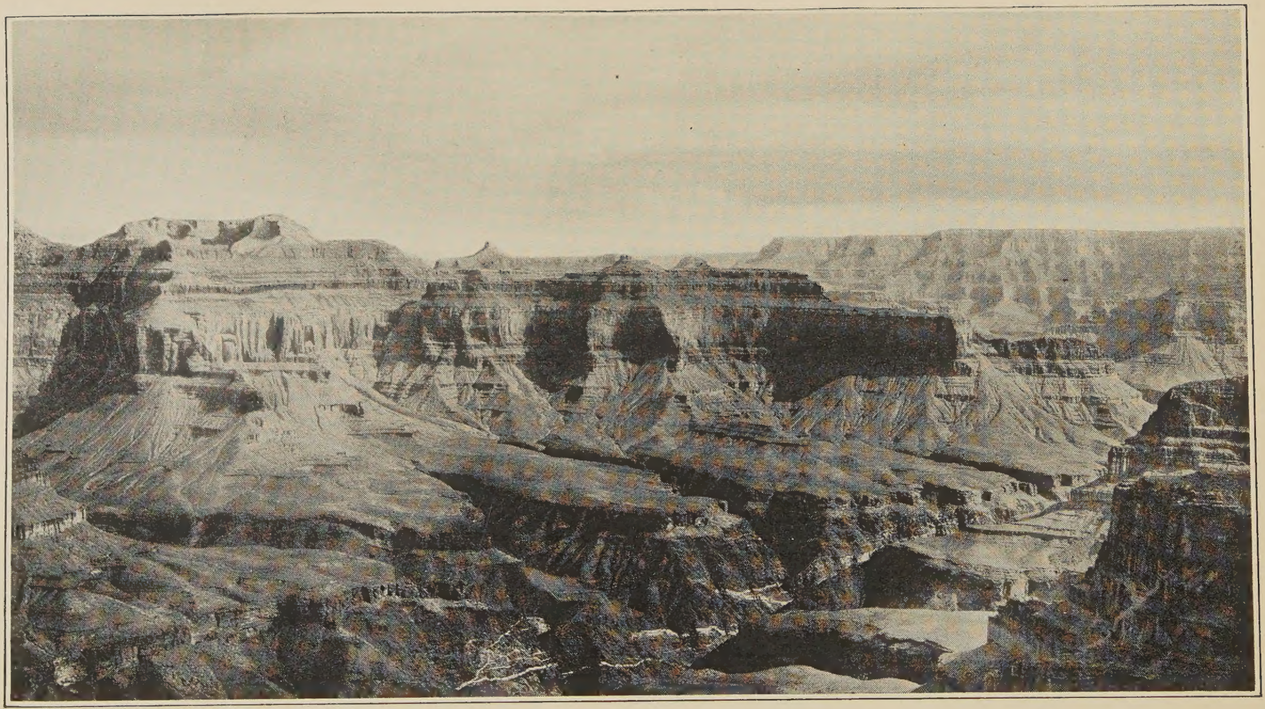

THE GRAND CANYON OF THE COLORADO, ARIZONA

Courtesy of the United States Geological Survey

THE EARTH AND ITS HISTORY

A TEXTBOOK OF GEOLOGY

BY

JOHN HODGDON BRADLEY, Jr., Ph.D.
ASSOCIATE PROFESSOR OF GEOLOGY IN THE
UNIVERSITY OF MONTANA

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PREFACE

This volume has grown out of the author's need for an elementary textbook of geology for use in a short course. It was written for the general student who desires to be intelligent about the earth. The material is arranged with an eye to general principles rather than to special applications. Such an arrangement necessarily departs from current practice in standard textbooks designed for use in a year's course. This volume is an attempt to write a book expressly for the short course, for those teachers and students who have found the larger books too technical and too involved. An endeavor has been made to eliminate unfamiliar nomenclature wherever advisable, and to make the presentation vivid where vividness is compatible with truth.

Many of the drawings and photographs were made especially for this book. The author is under obligation to Dr. Stuart Weller and to Mr. A. W. Slocom for several photographs of fossils in the Walker Museum of The University of Chicago; to Professors R. T. Chamberlin, D. J. Fisher, and Alfred Romer of The University of Chicago for similar aid; to Mr. Royle C. Rowe and Mr. E. Raisz for many special services in the preparation of diagrams.

The section in Chapter VI dealing with the age of the earth was written by the author in somewhat different form and published in the *Scientific Monthly*. It is used here with the permission of that magazine. Not all the sources of this book can be mentioned. Many textbooks of geology have been freely consulted, as well as publications of various geological surveys. The writer is duly grateful to the authors of these works.

Dr. N. J. Lennes of the Department of Mathematics at the State University of Montana has been critically interested in the work. Mr. Nelson Sayre of the Department of Geology at the University of Pennsylvania has kindly read Chapter VII and made some valuable suggestions. To these men and to his colleagues in geology the writer is indebted. He is deeply grateful to Dr. Charles H. Clapp, president of the University of Montana, whose many suggestions, both geological and pedagogical, are embodied in this book. Dr. Clapp likewise generously read the entire manuscript before it went to press.

JOHN HODGDON BRADLEY, JR.

University of Montana
Missoula, Montana

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THE EARTH AND ITS HISTORY

CHAPTER I

THE EARTH AS IT APPEARS TODAY

Geology is usually defined as the science that treats of the earth and its inhabitants. By this definition something of the vast scope of this science becomes immediately apparent. A general picture of the earth shows a great mass of passive material obedient to certain definite laws of movement, actuated by forces of a purely physical nature, and subject to the changes which have forever been the lot of all lifeless, or *inorganic,* matter. Such changes and the laws which control them have been known, and are being made known, through the long and patient labors of the sciences of astronomy, physics, and chemistry. Without the basic teachings of such sciences geology as a true science could never have been established; with their aid modern geology is able to attack more effectively the many problems which arise from the physical nature of the earth.

But the study of the astronomy, physics, and chemistry of the earth brings us only through the beginning of geology. Very early in the history of our globe living creatures appeared, subject not only to the laws elucidated by the physical sciences but also to the laws of biology. The sciences of botany and zoölogy are therefore invoked so that those early inhabitants of the earth may be better understood. It can be truly said that the science of geology deals with and includes phases of nearly every other science; and for that reason geology may be considered broader in scope than most other sciences.

An unfortunate result of the broad scope of geology is the division of its vast field into subsciences. This tends to obscure the dominant theme of the subject proper; namely, the *history* of the earth and its inhabitants. The interpretation of the sequence of events from the origin of the earth as a distinct entity in the solar system, through many changes to the time when life first appeared, and down through the long ages to the present, is the chief concern of the science of geology. Problems of a special nature appear all along the way from the beginning. The study of the earth as a planet in the solar system and its relation to other planets is approached both through the science of astronomy and through that of geology. At this common meeting ground a new subscience has been developed, that of *cosmic* or *astronomic geology*. In the same way there have been developed the subsciences known as *structural geology*, which treats of the arrangement of the material forming the framework, or skeleton, of the earth; *petrology*, which considers the individual bodies of rock in this framework; *petrography*, which deals with the minerals, their origin and relationships in rocks; *mineralogy*, which considers the structure and other characteristics of the individual minerals. *Meteorology*, the science of the atmosphere, and *oceanography*, the science of the sea, are correctly included under geology, since the air and the oceans are just as truly parts of the earth as the rocks. The application of geological knowledge to commerce and industry is known as *economic geology*. The history of the ancient life of the earth is called *paleontology*. The study of the agencies which produced the present aspect of the earth's surface is *physiography*. Other subsciences have been defined, such as *historical geology* in a restricted sense, which treats of the development of the principal land masses and the evolution of life. It can be seen that these subdivisions overlap. They are all interdependent and lead ultimately to the knowledge which is of foremost importance — the history of the earth and its inhabitants. A desire for this knowledge is and has been the controlling philosophy of the science of geology.

THE ATMOSPHERE

When the earth is considered as a whole, it is seen to be divided naturally into three parts which appear as continuous concentric spheres around a common center. These spheres are called (1) the *atmosphere*, (2) the *lithosphere*, and (3) the *hydrosphere*.

Constitution and weight. The atmosphere is made up almost entirely of gases and vapors, but it also contains such solid impurities as dust and microscopic plant and animal spores. The materials of the atmosphere are varied and irregularly but intimately mixed. Certain gases appear to be permanent inhabitants of the atmospheric zone, of which the inert nitrogen and the active oxygen are the most abundant. Nearly the entire bulk of the atmosphere consists of these two gases, nitrogen constituting about 78 per cent of the volume and oxygen about 21 per cent. Carbon dioxide is present in measurable quantities (about $\frac{3}{10,000}$ of the entire volume), and rare gases, such as argon and helium, are also represented. Certain vapors, notably water and emanations from volcanic vents, are transitory inhabitants of the atmosphere.

The weight and mass of the atmosphere, compared with that of the hydrosphere and the lithosphere, are negligible, as can easily be imagined when the extremely tenuous nature of air is considered. Nevertheless the weight and mass of the atmosphere are not negligible when compared with human standards of measurement. It has been estimated that the atmosphere weighs five quadrillion tons, and it is definitely known to exert a pressure of nearly fifteen pounds to the square inch, or a ton to the square foot, on the surface of the earth at sea level. This tremendous pressure is compensated, fortunately enough for living creatures, by equal pressure within the bodies of plants and animals, so that they have no perception of the pressure of the atmosphere. It is at once apparent that an exceedingly tall column of this excessively light material must exist to produce such pressure at its base. The thickness of the atmospheric zone is not known, but at fifty miles from the earth's surface air is so attenuated that its properties escape detection. It would seem that away from the earth's surface the atmosphere grows continuously thinner, until at a distance of fifty miles it no longer has body enough to be of interest to us as a factor in geologic processes.

Source and distribution of atmospheric heat. The major source of heat in the atmosphere is the sun, although some little heat is obtained from the interior of the earth and in other ways. Largely through the agency of the water and carbon-dioxide content, the atmosphere retains this heat. The atmosphere receives very little of the heat given off by the sun, the estimated amount captured by the earth being $\frac{1}{2,000,000,000}$ of the total. This relatively small percentage is precisely the correct amount to render the earth habitable by living creatures. Concretely, the heat received by the earth from the sun each year, if equally distributed, would melt a layer of ice about 141 feet thick over the entire surface of the earth, or evaporate a layer of water 18 feet deep. The temperature of space is thought to be −273° C.; so it can be seen that this small fraction of solar heat brings the temperature of the earth from the unthinkable cold of outer space to that temperature which is hospitable to living things. A little more or less absorption of solar heat would make life on earth impossible.

Three distinct processes are involved in the distribution of heat in the atmosphere after it has been received from the sun. These are known as *radiation*, *conduction*, and *convection*. When the sun shines upon the surface of the lithosphere, a certain amount of the heat of the sun's rays is absorbed directly. This method of heat transference is called *radiation*. It is familiar to everyone who has warmed himself by the side of a camp fire. In the same way the land gives up to the atmosphere by radiation some of the heat it receives from the sun. The familiar example of heat *conduction* is a bar of iron heated at one end soon becoming warm at the other end. The atmosphere in contact with the land is warmed in much the same manner, provided, of course, that the surface of the land has a higher temperature than the air above it. When air is warmed in this manner, *convection* currents are set into movement, the heated air expanding and rising to make way for the colder air above, which is heavier and sinks. In identically the same way the air in a room is put into motion by convection currents arising from the warm air issuing from a radiator or a hot-air register. The process of convection is perhaps of the greatest importance in its effect on the distribution of heat in the atmosphere.

While some of the luminous heat radiated from the sun is absorbed directly by the atmosphere, it is the nonluminous heat radiated from the land which is most easily absorbed by the air. Water is heated from four to five times more slowly than land for the following causes: (1) the mobility of water allows the dissipation and dissemination of absorbed heat by convection; (2) while land absorbs much of the heat of the sun's rays, water, being a good reflector, turns much back into the atmosphere; (3) on account of the evaporation at the surface, during which process heat is lost, water loses heat in a way that land does not; (4) water is a better conductor of heat than land, so that in water the solar heat is better distributed, whereas in land it is held near the surface. Other reasons might be added, but enough has been said to show that the air over the land is heated more highly and, for nearly the same reasons, cooled more quickly than the air over the water. For this reason continental climates show far greater annual variations than do oceanic climates. The variation in temperature of land masses is a potent factor in the geological evolution of continental forms.

Work of the atmosphere. Through direct heating by the rays of the sun and subsequent radiation, rocks of the earth's crust are made to expand and contract, with a corresponding change in density. Since rock is a poor conductor of heat, only the outer surface is affected; but in time the effect of repeated heating and cooling of the surface causes much rock to be shattered. Water on freezing expands one tenth of its volume, and we shall see that because of this peculiarity much destructive geological work is accomplished by water under the control of changes in atmospheric temperature. The geological work of the atmosphere is manifold, but can be grouped into (1) physical work and (2) chemical work. The first includes the transportation and deposition of dust and sand, deflation, abrasion, and other effects of wind on land masses; the second includes effects of the active principles of the air, chiefly oxygen and carbon dioxide, on rock matter.

Movement of the atmosphere. Physical work is accomplished only when the atmosphere is in motion. Such motion is the inevitable result of different pressures exerted by air in different places and at different times in the same place. *Moisture* and *temperature* are the two most important factors in the control of atmospheric pressure. Water vapor is only five eighths as heavy as dry air, so that moist air is lighter than dry air. We have seen that water is unequally distributed in the air; and since dry air is heavier than moist air, the atmospheric pressure over regions that are notably dry, such as deserts, is higher than that over moist lands and oceans. The temperature of the surface of the earth varies from place to place and from time to time in the same place. Since air is heated largely by the surface on which it rests, it is unequally heated. The weight of air varies with its temperature, hot air being lighter than cold air, so that different pressures are developed in different parts of the atmosphere. A third factor, the *rotation of the earth,* although not the cause of inequalities in pressure, is important in controlling their distribution. Movements of the atmosphere due to difference in pressure are known generally as *winds.*

It is a well-known fact that the earth's atmosphere is unequally heated, the air in low latitudes being heated more than that over the polar regions. This condition is determined by astronomic causes and probably has existed for a great length of time. The result is a tendency for the warmed equatorial air to expand, rise, and move toward the poles. On the other hand, the air over regions of greater pressure to the north and south tends to move along the bottom of the atmosphere toward the equator. In this way a constant equatorward movement in the lower air is established. These are clearly *horizontal* movements, which are accompanied by the rise of the warm equatorial air and the descent of the cool polar air in *vertical* movements (Fig. 1). This is the fundamental pattern upon which the entire circulation of the atmosphere is based. Various factors modify the scheme, chief among which are the rotation of the earth and the unequal heating of land and water areas in the same latitude.

The result of these fundamental movements of the air is the development of *belts of high pressure* in intermediate latitudes (approximately 30 degrees north and south). It is here that the cool polar air, which descends and flows equatorward, meets the warm equatorial air, which rises and flows poleward. Not only the outward flow but the outward crowding of the expanded air in the equatorial belt is largely responsible for this increase of pressure to north and south, while the region near the equator remains under low pressure. Likewise, two areas of low pressure exist in high latitudes. Since air naturally flows from areas of high pressure to areas of low pressure, there would be a tendency for air to move from the extratropical belts of high pressure both toward the poles and toward the equator. This tendency is diagrammed in Fig. 2. The rotation of the earth, however, deflects the currents of the air to the right in the high latitudes and to the left in the low latitudes (Fig. 3). The combined effect of temperature, pressure, and the rotation of the earth is the production of *wind belts*. The borders of these belts are extended or restricted according to the seasons.

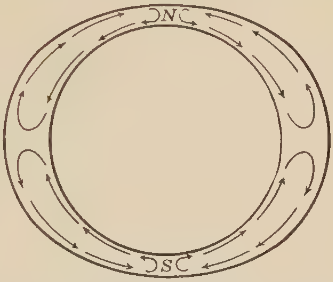

FIG. 1. Diagram illustrating the nature of air movement under unequal heating in different latitudes. (Reprinted by permission from "Physiography," by R. D. Salisbury. Published by Henry Holt and Company)

The poleward-moving winds in each hemisphere are turned toward the east and are known as *westerly winds*; those blowing toward the equator in each hemisphere are deflected toward the west and are known as *easterly winds*. Since these winds are dependent on the rotation of the earth and would be equally developed on any other planet which had an atmosphere, because of the rotational movement inherent in planetary bodies, they are together known as *planetary winds*. They are restricted to the lower zone of the atmosphere. The easterly planetary winds are called *trade winds*, because they are the most constant of all winds and always follow a "trade," or straight, course. Where these trade winds meet at the equator, a belt of calms known as the *doldrums* is produced. Another similar belt of calms, developed where the westerly winds meet the trades, is known as the *horse latitudes*. In calm belts the movement of the air is vertical rather than horizontal.

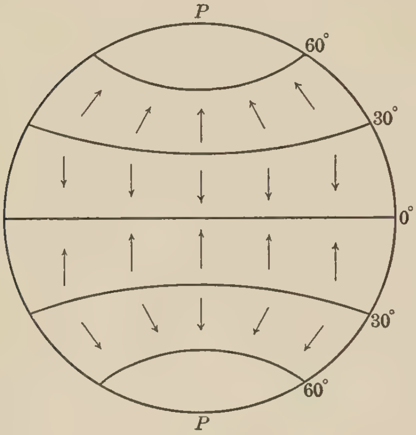

FIG. 2. Diagram showing how the lower air would move if the earth did not rotate. (Reprinted by permission from "Physiography," by R. D. Salisbury. Published by Henry Holt and Company)

The simplicity of the system of planetary winds is greatly disturbed by differences in temperatures of the air over land and sea. In some cases the planetary winds are completely overcome by seasonal winds such as the *monsoons* of southern Asia and the *land breezes* and *sea breezes*, which are often produced locally along seashores. Without going into the detailed mechanism of this type of winds, it can be said in general that winds develop where and when temperatures of land and sea are strikingly different, and these winds may locally or for a time be the dominant factors in the circulation of the air.

We have considered the general plan of the fundamental movements which dominate the earth's atmosphere. There occur, in addition, minor movements known as *storms*. An area of low barometric pressure from five hundred to one thousand miles across, toward which wind flows spirally inward, is called a *cyclone*. Conversely, an area of high pressure from which the wind passes spirally outward in all directions is called an *anticyclone*. Cyclones and anticyclones travel with the westerly planetary winds at the average rate of thirty miles an hour. More or less precipitation of rain or snow accompanies cyclonic areas, whereas the anticyclones are attended normally by clear weather. The study of the movement of storm centers is the basis of weather forecasting.

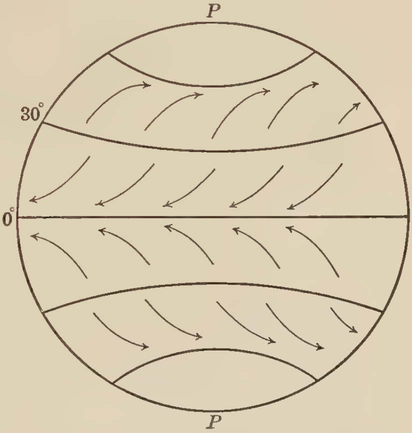

FIG. 3. Diagram showing the deflection of air currents by the rotation of the earth. (Reprinted by permission from "Physiography," by R. D. Salisbury. Published by Henry Holt and Company)

Cyclones in tropical regions often follow different routes of movement from those in temperate latitudes. These storms are sometimes called *hurricanes* in the region about the West Indies. The same type of storm is called a *typhoon* in the west Pacific and Indian oceans. If air is excessively heated locally over a moist land, a rapid condensation of water vapor with electrical discharges may result. This type of storm is called *thunderstorm*; it is always short-lived and moves along with the planetary winds of both hemispheres. The same conditions produce the more severe *whirlwinds* and *tornadoes*, which are perhaps the most effective instruments of rapid destruction used by the atmosphere on the lithosphere. Fortunately for man the duration of the tornado is brief, the area affected small, and the occurrence (except in a few regions) rare. About one hundred and fifty tornadoes of varying intensity are recorded annually in North America, mainly in Kansas, Missouri, Illinois, and Indiana.

The distribution of solar heat and moisture in the air and its control by air movements produce what is known as *climate* in any given locality. Climate is the sum of shorter-lived conditions in the atmosphere of any locality, which are known as *weather* conditions.

Moisture. Second only to temperature conditions, the moisture of the atmosphere is important as a geological agent. It is the moisture in the air which furnishes frost, clouds, fogs, rain, hail, and snow, upon which life on earth is so largely dependent. The intimate relationship between atmospheric moisture and temperature has been seen; without its water vapor the air could not hold the heat radiated from the sun. The chief source of water in the atmosphere is the hydrosphere. All moist surfaces are constantly giving up water to the air by *evaporation,* a process whereby molecules of water change to molecules of water vapor. Even the apparently dry parts of the lithosphere lose by evaporation the water which is locked up in the minute pores in rocks and in the interstices in unconsolidated material, such as soil.

If moist air is carried to regions of lower temperature, it loses its water vapor by *condensation,* a process the direct reverse of evaporation. The result of condensation is the *precipitation* of moisture in some form or other, controlled always by temperature conditions. If the temperature of the land or of objects on it falls below that of the surrounding air, atmospheric moisture is condensed as *dew.* If the temperature of the air falls below the freezing point of water (32° F.), moisture may condense on the surface of cold objects as *frost.* Sometimes atmospheric vapor condenses but remains suspended in the air as *clouds.* If clouds rest on the surface of the earth, they are called *fogs.* When particles of atmospheric moisture become large and heavy enough to fall, the result is *rain.* If rain passes through a layer of cold air before reaching the earth, it is apt to freeze and be precipitated as *hail.* If the air is sufficiently cold, its moisture may condense and be precipitated on the earth as *snow.*

Importance of the atmosphere. As living creatures our interest in the atmospheric moisture is great. Without it the heat of the sun would reach the earth with undiminished intensity by day, only to be lost completely at night. If we succeeded in escaping the scorching heat of day, we should certainly perish in the bitter cold of night. It is the atmosphere, largely through its water content, that seizes the radiant energy of the sun, distributes and mollifies it, and retains it. Without an atmosphere of the correct constituency, life on earth or on any other planet would be unthinkable.

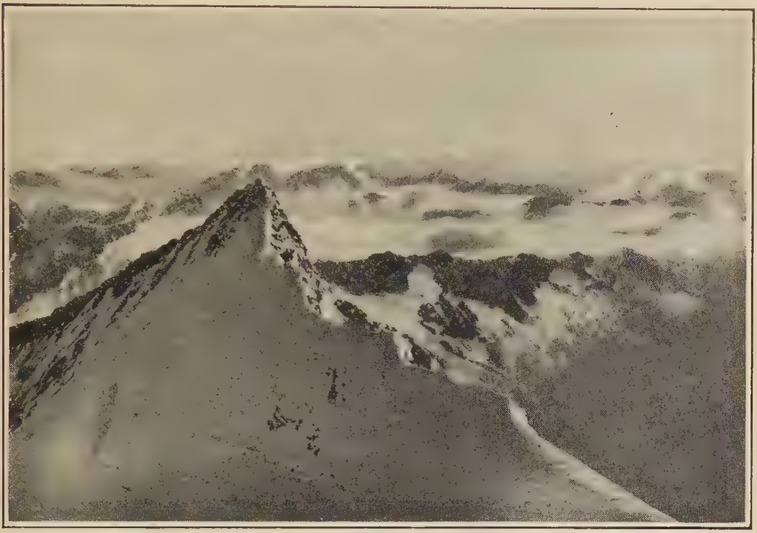

FIG. 4. Clouds resting on mountain tops, Swiss Alps. (Courtesy of Dr. R. T. Chamberlin)

Although the atmosphere gives protection to the living creatures on the earth, its general effect on the crust of the earth is that of destruction. Innocuous enough while in a static condition, it becomes a powerful geological instrument of destruction when moving. Moving portions of the atmosphere, or winds, are influential in moving rock material which has been loosened by other agencies, as well as in attacking and destroying more compact rock bodies. Due to certain attributes of the atmospheric gases and vapors, a variety of chemical as well as physical tasks are performed. These are largely to the end of destroying the existing form of the earth's crust and will be discussed more fully in a later chapter.

THE HYDROSPHERE

The hydrosphere is nearly as continuous as the atmosphere. Because of irregularities of the earth's surface, most of the water is gathered into the larger depressions. These depressions, which are called *ocean basins,* are all connected and interdependent, and act as a unit in response to such influences as lunar tides or large influxes of water derived from the melting of continental ice caps. Somewhat more than 70 per cent of the earth's surface is occupied by ocean water, which collectively is known as the *marine portion* of the hydrosphere. In addition to the water in the ocean basins, the upper part of the lithosphere is permeated with a fairly continuous film of water, constantly searching through the pores and crevices of rocks and joining the ocean waters at the margins of the continental masses. This film of the hydrosphere is known as the *ground water*, or *underground water*, and, with the surface land waters of streams and lakes, completes the spherical form of the waters of the earth's crust. Ground water, inland seas, lakes, and rivers constitute the *continental portion* of the hydrosphere.

The hydrosphere at its deepest point in the Nero Deep, off the island of Guam in the Pacific Ocean, is 31,615 feet. If the irregularities of the ocean bottoms and continental surfaces were smoothed, and the surface of the solid earth were perfectly spheroidal, it is estimated that sufficient water is present in the hydrosphere to form a universal ocean not quite two miles deep.

Importance of the hydrosphere. The greatest part of geological history has been written by water. The waves of the sea are forever gnawing at the edges of the land; streams and underground waters are unremitting in their effort to reduce the lands to flatness by the destruction of the high places and the filling of the low. The ocean basins are the final repositories for materials worn from the lands. Throughout geological history both the hydrosphere and the atmosphere have united in the effort to denude the lands and fill up the ocean troughs. This combined attempt has never been entirely successful, because of the timely intervention of another factor in earth evolution. This factor, which tends periodically to elevate the continental masses, will be considered in detail under the chapter on processes of deformation.

Marine Waters

All the water confined to the ocean basins is called *marine.* Although the waters of the various ocean depressions mingle freely and, in a sense, act as a unit, the troughs themselves vary largely in regard to form, size, and distribution with reference to the continents. On the basis of these differences the marine portion of the hydrosphere can be divided into certain natural groups. Our modern classification of seas harks back to the Greeks, whose knowledge of the sea was limited to the Atlantic, or great *outward* sea, and the Mediterranean, or *inward* sea. We still adhere to the ancient idea of the great outward sea as typified by the Atlantic and characterized by the word *ocean.* The long, narrow, deep troughs filled with sea water and lying between continents are still called *mediterraneans.* Broad depressions along the margins of continents are called *gulfs*; those which extend more into the continental masses are called *bays.* *Straits* are narrow bodies of marine water between projections of two neighboring land masses. Shallow seas formed by the transgression of ocean water upon portions of a continental mass which have subsided are called *epeiric* seas.

Sea level. Since the seas are all connected, factors which tend to affect one are likewise felt in the others. In contrast to the land surface, the surface of the sea is essentially smooth.

This smoothness has led to the use of the term *sea level* for the level of the surface of the sea, and from this plane are measured all elevations on land. The surface of the sea is actually not level but curved, with a tendency toward spheroidal form. This form is only imperfectly realized, because of the attraction of the land for the water and because of other disturbing influences such as lunar tides and local inequalities produced by atmospheric causes.

Composition of sea water. Sea water is never pure in the sense that it is composed entirely of water. The water of the sea in all places includes dissolved mineral matter and gases. Nearly 3½ per cent of the weight of sea water consists of solid material in solution. Of this, about 78 per cent is common salt, which gives to sea water its characteristic saltiness. Many other mineral substances are present to a lesser degree, notably magnesium chloride, magnesium sulphate, calcium sulphate, and potassium bromide. These are listed in the order of their abundance. Many other elements, some of them quite rare, have been detected in much smaller quantities by chemical analyses of sea water. These are iodine, fluorine, arsenic, silicon, boron, lithium, rubidium, cæsium, barium, strontium, aluminum, iron, manganese, copper, zinc, silver, gold, and radium. Some of these elements are found not only in the sea but in the skeletons of plants and animals that make their homes in the sea. A few elements, notably lead, nickel, and cobalt, have been detected in the skeletons of such sea organisms but have not been found in the water itself. In addition to mineral matter the sea has various gases dissolved in it, principally nitrogen, oxygen, and carbon dioxide in small but varying percentages.

Source of mineral matter. Nearly all the mineral substances of the sea were derived from the rocks of the lithosphere. (1) Rivers of today are bringing mineral matter into the oceans. This material was dissolved from the rocks of the continents by the slow but unremitting attack of ground water, which entered the rivers of the earth with its dissolved load, largely through springs. Rivers of past ages have similarly received mineral matter from the rocks and deposited it in that great wastebasket of the earth, the sea. Undoubtedly much of the present quota of mineral matter was accumulated through the long-continued feeding of the sea by rivers. (2) In addition to rivers, volcanic eruptions through long ages of time must have contributed much mineral matter to the sea, particularly the eruptions of those volcanoes that are known to exist in many places on the ocean floors. (3) Lastly, the sea water itself must have dissolved a great deal of mineral matter from the lithosphere where it is in contact with rock material at its bottom and sides.

Source of gases. Unlike the mineral matter, the gases in sea water are derived largely from the atmosphere. The three chief gases — oxygen, nitrogen, and carbon dioxide — are disproportionately extracted from the air, both (1) because they are present there in different amounts and (2) because they are dissolved by water with varying degrees of ease. Nitrogen is the least soluble of all, oxygen is more soluble than nitrogen, and carbon dioxide is more soluble than either. Despite the low solubility of nitrogen it is the most abundant gas in sea water as it is in air, constituting about 37 per cent of all the dissolved gases. In like manner, about 33 per cent is represented by oxygen and about 16 per cent by carbon dioxide. The total amount of nitrogen and oxygen dissolved in the sea is but an insignificant fraction of the amount in the atmosphere, but that of carbon dioxide is estimated at about eighteen times the amount in the air. This is due to the fact that much carbon dioxide is given to the sea by volcanoes and through the life processes of organisms which live in the sea.

Temperature of the sea. The temperature of the sea varies with the latitude, as does that of the continents, the mean range being from about 80° F. in the equatorial regions to 28° F. in the polar regions. Unlike the land, the temperature of the sea decreases in depth except where the surface waters are near the freezing point. The surface waters as well as the deep ocean waters have their temperatures modified by currents, so that general decrease in temperature from the equator to the poles and from the surface downward is locally disturbed. Estimates have been made which show that the bulk of sea water is cold, the average temperature near the bottom being below 35° F. Nearly the whole mass of sea water is below 40° F. This is easily explained by the fact that (1) the sun radiates heat to a depth of only six hundred feet into the sea, and the heat thus imparted is quickly dissipated; (2) because of the poor conductivity of water, little heat is absorbed from the contact of the sea with its bottom and sides; (3) surface waters are constantly being chilled by influx of cold polar currents, and when these cold waters, which are heavy, sink to the bottom, the general temperature of the sea is lowered.

Movements of the sea water. The movements of sea water can be classified as (1) *currents*, (2) *waves*, and (3) *tides*.

Currents. Ocean currents are due to a variety of causes, and in some cases to a combination of causes. One of the major causes of currents is local differences in the density of sea water. Such inequalities may be produced by (1) local differences in the mineral content, or *salinity*, of the water and (2) local variation in temperature. These differences in their turn are caused by local variations in (1) evaporation, (2) rainfall, or (3) melting snow or ice. In connection with these the configuration of the ocean basins, while not the cause of currents, is an important factor in influencing their courses. Other agencies completely without the region of the hydrosphere, notably wind, are often contributory causes.

Convection currents established in the sea as a result of unequal heating by the sun are greatly modified by the winds and the continental masses. The general result is shown in Fig. 5. In the equatorial regions of both the Atlantic Ocean and the Pacific Ocean, under the influence of the trade winds, the surface waters are driven westward. These movements are slow and are known as the *equatorial drifts*. Where the Atlantic equatorial drift impinges on the north coast of South America it divides, part turning to the southwest and the other part to the northwest. A large portion of the latter flows into the Caribbean Sea and the Gulf of Mexico; out of the Gulf, from the narrow passageway between Florida and Cuba, issues the well-defined current known as the *Gulf Stream.* At this point the Gulf Stream flows with a velocity comparable to a great land river such as the Mississippi, but becomes wider, deeper, and slower as it creeps northward along the eastern coast of North America. The outline of this continent tends to deflect the current to the eastward into mid-ocean. Before reaching the coast of Europe it divides and spreads. Between the point of debouchure from the Straits of Florida and the place of division in the North Atlantic, the Gulf Stream decreases in velocity from more than seventy-five miles a day to less than ten miles. After division it is no longer a stream in the strict sense, but a drift, such as that from which it took rise. Upon dividing, one part is deflected northward into the Arctic Ocean, and the other southward to rejoin the westward equatorial drift.

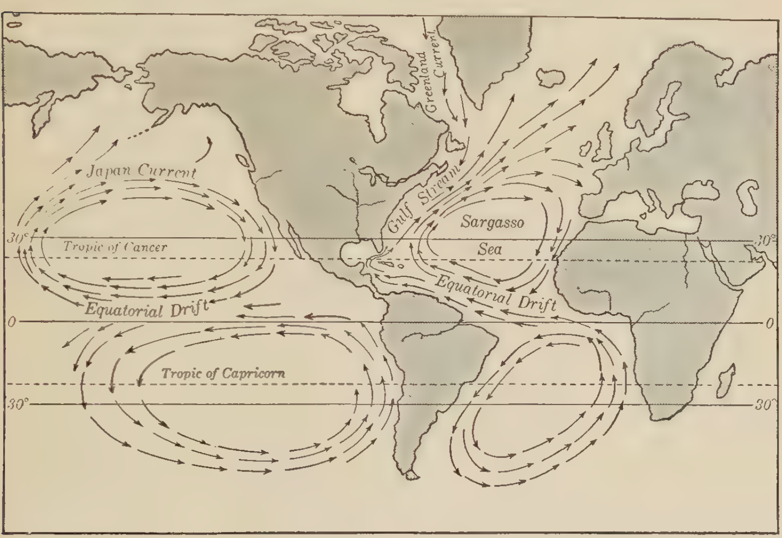

FIG. 5. Diagram of main ocean currents and drifts. (From Shimer's "An Introduction to Earth History")

Unlike the circulation of the Gulf Stream, that part of the Atlantic equatorial drift which is turned southward along the eastern coast of South America completes its circuit by turning to the left. In the North Atlantic a current of diametrically opposite nature emerges from the Arctic Ocean, flows down the coast of Greenland between Labrador and Newfoundland, and gradually passes under the warm waters of the Gulf Stream off the coast of New England. This current of cold water is called the *Labrador Current.*

In the Pacific Ocean currents analogous to those of the Atlantic exist. The equatorial drift of the Pacific gives rise to a current comparable to the Gulf Stream, known as the *Japanese Current.* In like fashion a drift exists in the Indian Ocean. As in the Atlantic, compensating undercurrents of cold water in these oceans, produced by the differences in temperature between high and low latitudes, flow from the polar regions toward the equator, gradually becoming warmer, saltier, and deeper.

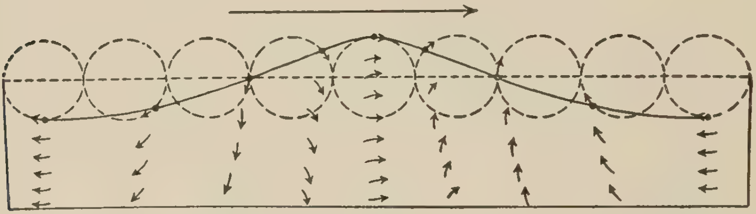

FIG. 6. Diagram illustrating the movement of water in waves. (Reprinted by permission from "Shore Processes and Shoreline Development," by D. W. Johnson. Published by John Wiley & Sons, Inc.)

The large arrow shows the direction of wave advance

Waves. Winds blowing over the surface of the sea produce movements in the water called *waves.* The top of a wave is its *crest*; the hollow between two waves is the *trough.* The distance from crest to crest is known as the *wave length,* and the vertical distance between crest and trough is the *wave height.* The time taken by a wave crest or a wave trough to travel a wave length is called the *period* of the wave. In the open sea, where the bottom or shore does not affect the movement of waves, each particle of water moves in a closed circle; so while the *form* of the wave marches onward, the water, moving in orbits, does not advance to any marked extent. In Fig. 6 the movement of water in waves is diagrammed. It will be seen that movement is *forward* in the crest and *backward* in the trough, and that the diameter of the orbits in which the water of the wave moves is equal to the height of the wave.

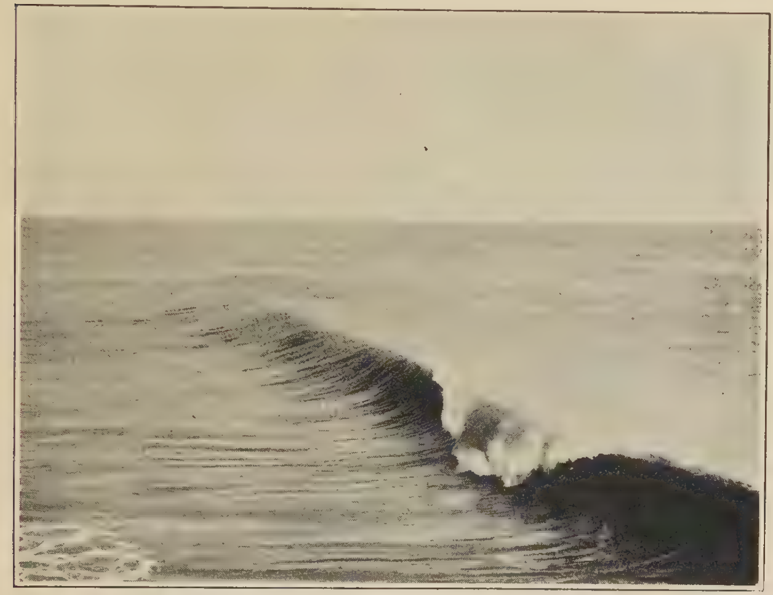

FIG. 7. A wave breaking alongshore. (Reprinted by permission from "Shore Processes and Shoreline Development," by D. W. Johnson. Published by John Wiley & Sons, Inc.)

As waves from the open ocean approach shallow water the velocity and length of each wave are decreased, while the height is increased. This results partly from dragging on the bottom. Eventually a place is reached where the depth is so shallow that the water cannot complete its orbital movement. The wave, no longer able to maintain its form, "breaks" along the front in *surf*. This water runs back into the sea down the slope of the shore, causing *undertow*. Much of the destructive work of the sea is done through the agency of wind-driven waves.

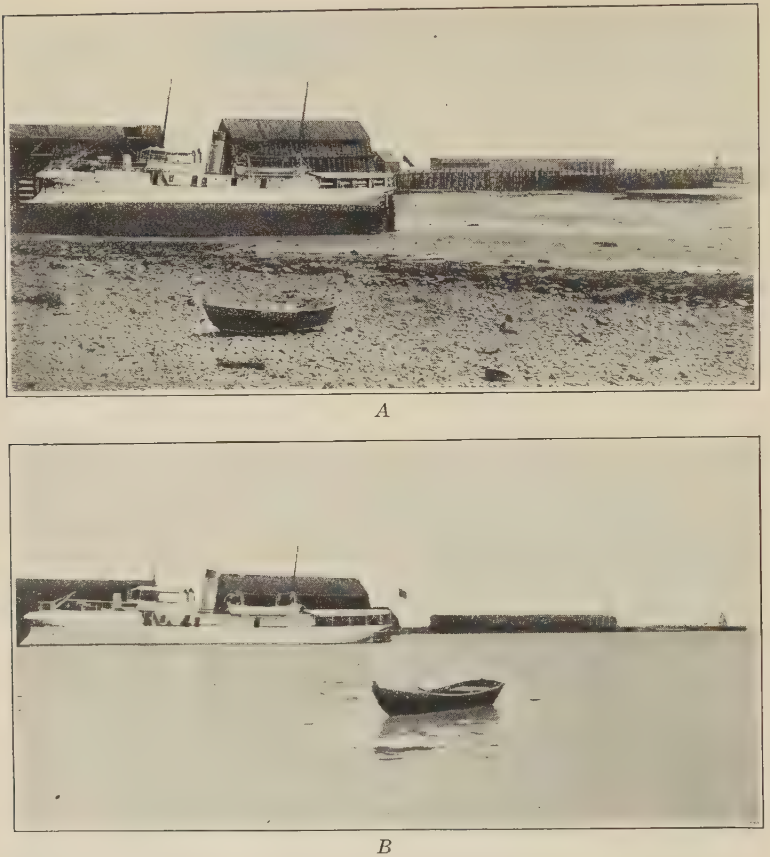

FIG. 8. Tides of the Bay of Fundy. (Courtesy of the Geological Survey of Canada)

A, low tide; *B*, high tide

Tides. Twice in every twenty-four hours and fifty-two minutes the waters of the ocean rise and fall in periodic movements called *tides*. These movements, although felt throughout the entire body of the sea, are best observed along coast lines, where they are most strongly developed. Tides in the open ocean seldom exceed three feet in vertical movement, whereas along coasts they may be from four to six times as pronounced. These tidal movements are apt to be best developed in bays, particularly in the Bay of Fundy, where at one point a difference of fifty-three feet between the elevation of the surface of the sea at low tide and at high tide has been measured.

Many years ago it was observed that the periodicity of tidal movements corresponded with that of the moon in revolving about the earth. That the earth was made actually to bulge periodically through the double attraction of the moon and sun was conclusively proved by Newton more than two centuries ago. The effect of the bulging is felt largely in the marine portion of the hydrosphere, but it is known to a lesser extent in inland lakes and seas. The less plastic lithosphere is under the same pull as the sea but, for obvious reasons, does not yield in a similar way.

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CONTINENTAL WATERS

We have seen how most of the water falling from the atmosphere settles in the great marine basins. A large part of the rain which falls on the land runs off directly into the rivers and thence to the sea. Some of the rain water, however, does not immediately reach the sea, but abides on the continents for a time in depressions known as *lakes*; some penetrates the rocks of the lithosphere at once, there to move sluggishly through pores and crevices, and eventually to issue as *springs* and *wells*, join the rivers, and at last enter the sea. *Ground water* is nearly everywhere present in the upper part of the earth's crust and, together with lakes, inland seas, and rivers, constitutes the nonmarine, or continental, portion of the hydrosphere.

Ground water. The ground water is the least conspicuous division of the hydrosphere, but it is by no means the least important in a geological sense. Its importance to man is likewise great when one thinks of the millions of wells in the United States alone which have been made possible by this great reservoir of water. Drought may come and ruin the crops of the farmer; but the well that quenches his own thirst will ordinarily survive the drought, for although the ground water is dependent on rain for its existence, nevertheless its sources are many and are not dependent on local precipitation. The great semiarid plains of western North America are in most places well watered *underneath* by moisture that falls in the Rocky Mountains to the west and later joins the ground water, part of which in that region moves eastward below the plains.

Porosity. Ground water is made possible by the fact that all rocks are more or less porous. Since there are many kinds of rocks, no two of which are exactly the same in regard to composition, attitude, and the interstices within them, there is variation from place to place in the abundance, composition, depth below the surface, and rate of movement of the underground water. Very small openings, or *pores*, are common to all rocks. Through these pores the ground water moves, and the *porosity* of a given rock is the percentage of the total volume of the rock occupied by such openings. Many rocks have larger openings, cracks or fissures, which increase their porosity and aid the accumulation and circulation of ground water. The porosity of rocks is highly variable. Closely knit rocks, such as granite, may have a porosity as low as a fraction of

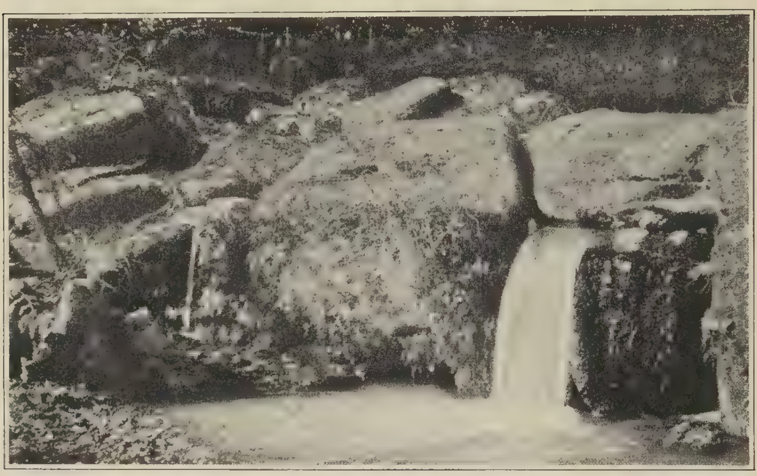

FIG. 9. A spring emerging from limestone. (Photograph by M. L. Fuller. Courtesy of the United States Geological Survey)

1 per cent. On the other hand, loose, coarse material such as that deposited at the mouths of rivers with steep gradients may have a porosity of from 80 to 90 per cent. Consolidated rock material seldom has a porosity in excess of 40 per cent, and any rock with more than 20 per cent of its bulk given over to open spaces may be considered unusually porous. The (1) size, (2) shape, and (3) arrangement of the grains in a rock determine its porosity. If a rock is made up of large grains all of the same size (as is true in some gravels), the porosity is apt to be greater than in the case of a rock made up of uniformly small grains (as is true in most clays). It follows, then, that in a rock made up of large and small grains, such as a mixture of gravel and clay, the porosity is greatly reduced. The amount of variation in the size of the grains composing a rock is called the *assortment*, and is perhaps the most important factor in the control of a rock's porosity (Fig. 10). The shape of the grains of a rock depends on the minerals of which it is composed; it naturally varies within a given rock and from rock to rock. In general, irregularity in shape makes possible a larger range in porosity, and in many rocks porosity is increased by irregularity of shape. Most of the water-bearing rocks are made up of fragments of rock material that have been more or less rounded by the wear of water and wind before they were deposited and cemented. Fig. 11 shows what

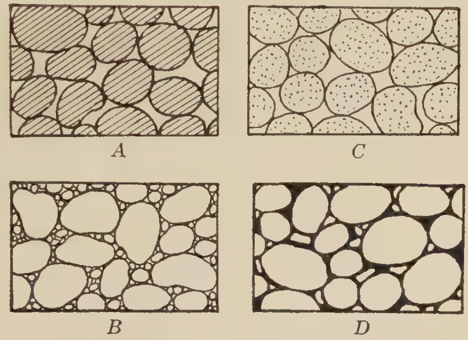

FIG. 10. Diagram showing how assortment influences porosity. (After O. E. Meinzer. Courtesy of the United States Geological Survey)

A, a well-sorted sedimentary deposit having high porosity; *B*, a poorly sorted sedimentary deposit having low porosity; *C*, a well-sorted sedimentary deposit consisting of pebbles that are themselves porous so that the deposit as a whole has a high porosity; *D*, a well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices

C100

variations in pore space of such a rock may result from different arrangements. In addition to the size and shape and arrangement of particles in a rock, the (4) nature of cementation and (5) compacting to which the rock has been subjected after its deposition, and (6) the amount of mineral matter eaten out of the rock by the percolating waters, help to control the porosity. Finally, (7) the size and abundance of fractures in a rock influence the amount of water it can absorb.

Permeability. While the amount of water that a rock can absorb is determined by the degree of its porosity, the ease with which water moves through a rock is not entirely dependent on the percentage of open spaces in the rock. The principal forces that control the movement of water in rocks are (1) gravity, (2) capillary attraction, and (3) molecular attraction.

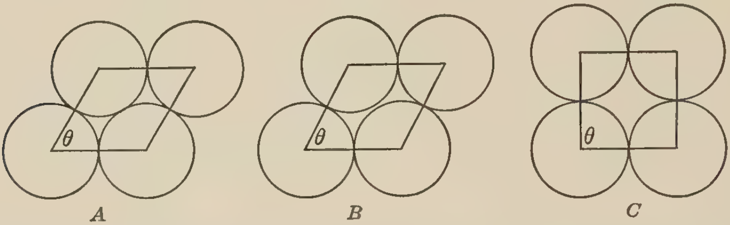

FIG. 11. Diagram illustrating the variation in pore space resulting from different arrangements of the particles in sedimentary rocks. (After O. E. Meinzer. Courtesy of the United States Geological Survey)

A, most compact arrangement; *B*, less compact arrangement; *C*, least compact arrangement

Openings in rocks are classified, according to size, into *supercapillary* (greater than 0.508 mm.), *capillary* (between 0.508 and 0.0002 mm.), and *subcapillary* (smaller than 0.0002 mm.) openings. If a rock has many relatively large openings (supercapillary), the flow of ground water through it is guided entirely by the dictate of *gravity*. If, on the other hand, a rock has openings of capillary size, the attraction of the walls of the interstices for the water produces friction known as *capillary attraction*, which retards the flow. If the openings in a rock are of *subcapillary* size, *molecular attraction* holds the water tightly within the pores, just as a magnet holds bits of steel. Even though the porosity of such a rock may be as high as 30 per cent, any movement of water through it is impossible. Such a rock is said to be *impervious* or *impermeable.* The *permeability* of a rock, therefore, is its capacity of allowing water to pass through. It is under the direct control of the molecular attraction set up in a rock by the size of its open spaces. Permeability is likewise influenced by pressure, for it is easily understood that a rock which does not transmit water under low pressure may do so if the pressure is greatly increased. On the other hand, if a normally permeable rock is compressed from all sides, it will not permit the flow of water through its interstices. Many shales and clays which are high in porosity are likewise impermeable because of the small size of their pores. It is important to remember that high porosity alone does not insure the free movement of ground water. After gravity has brought the rain water from the surface deep into the earth, and there caused it to filter for long distances laterally through rock with large pore spaces, to flow from springs, and to enter wells, its movement in rocks of small interstices is controlled by capillary and molecular attraction.

The water table. All porous rocks below a certain level are usually saturated with water. This water is generally under pressure induced by the pull of gravity, with the result that the water in the permeable rocks is constantly moving to lower levels. The rocks saturated by underground waters are said to be in the *zone of saturation.* Above this lies a zone which Meinzer has recently called the *zone of aëration.* Through this zone the water is drawn down from the surface by gravity, with the exception of that held back by molecular attraction. The upper surface of the zone of saturation is called the *water table* (Fig. 12). This level varies in depth (1) generally from place to place, and (2) locally with the slope of the land. In average moist regions in the United States it stands within 50 feet of the surface, in regions of limestone rock it is apt to stand between 200 and 300 feet below the surface, and in deserts and regions cut deeply by rivers it may lie as low as 3500 feet below the surface. In a few rare cases ground water is entirely absent. The water table is normally closer to the surface under valleys than under hills. Gravity is continuously at work to pull the water level down under hills, but molecular attraction and replenishment of supply by rain counteract this tendency to a large extent.

Bottom of ground water. The fact that in many deep mines ground water is conspicuously absent proves that the zone of saturation is a very thin film and of insignificant width compared with the radius of the earth. Rock pressure increases rapidly with depth, and estimates have been made of the depth at which all cavities and pores in the rock would be effectively shut to ground water. These calculations vary in their results, but all conclude that channels for the movement of ground water could not exist more than eleven miles below the surface of the earth. As a matter of fact, the great bulk of the ground water penetrates to no such depth, most of it being limited to the upper fifteen hundred feet of the earth's crust.

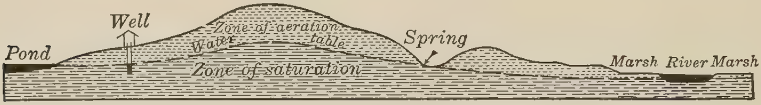

FIG. 12. Diagram illustrating the relationship of the water table to the land surface

Movement of ground water. Very little of the underground water flows through definite channels as water in rivers flows on the surface of the earth. Ground water percolates through the pores and fractures of rocks in a slow, nearly imperceptible movement. This motion depends upon (1) the inclination of the rocks through which the water flows, (2) the amount of water, and (3) the nature of the open spaces in the rocks carrying the water. If the inclination of a permeable formation carrying water between two impermeable formations is steeper in one place than in another, the rate of flow of the ground water will vary accordingly. If great quantities of ground water are present, the flow in places may be uphill because the pressure of the water locally overcomes the force of gravity. Rarely, underground channels exist through which water flows as freely as on the surface. Normally, however, water flowing through porous rocks moves slowly, the rate depending on (1) the size of the openings, (2) the pressure, (3) the relative abundance of openings in the rocks, and (4) the temperature of the water. Under very favorable conditions in Arizona it was found that ground water moved at the rate of nearly a mile in a year.

Work and fate of ground water. The result of the movement of ground water is the accomplishment of a certain amount of geological work of both a destructional and a reconstructional nature. The fate of ground water is ultimately to rejoin the sea and there lose its identity as a distinct factor in geological history. Always and forever following the course of least resistance, which is generally downward, it eventually finds its way into valleys occupied by rivers, or directly into the ocean troughs. Some enters inland seas and lakes and there (as in the case of the portion which terminates its career in the sea) either reënters the atmosphere by evaporation or is dissipated by mingling with the waters already in the great basins.

Inland seas and lakes. Various types of depressions exist within the borders of the continents. The warping and breaking of the rocks of the earth's crust often form basins on the continents; in places volcanoes, glaciers, and even living creatures have dammed up areas on the surfaces of the continents wherein water has accumulated. These waters form the second great division of the nonmarine portion of the hydrosphere. If very large they are called *inland seas*; if of lesser extent they are known as *lakes*. Some of these basins are deep, others are shallow; some are permanent, others are temporary. There is likewise a corresponding variation in the chemical composition of the waters, depending very largely upon the composition of the rocks over which or through which waters that feed such basins have passed. The work of lakes in building up and destroying the land surface, while not great, has been considerable.

Rivers. The last great group of continental waters is the rivers. Least of all the divisions of the hydrosphere in volume, they are by far the most important in respect to the work accomplished. The chief agency of land sculpture, rivers are largely responsible for the striking differences in the topography of the ocean basins and the continental protuberances. The history of rivers is long and varied, but is always intimately associated with the history of the lands over which they flow. As in the case of ground water and lakes, the source of their water is the moisture of the atmosphere, either directly or indirectly; and their fate, like that of ground water and lakes, is to empty their burdens into the sea and mingle their waters with the all-embracing flood of the oceans. Since the careers of rivers are so intimately related to the evolution of the lands, and since they are more important for what they do than for what they are, they will be treated more fully in a later chapter.

THE LITHOSPHERE

The lithosphere is the rocky framework of the earth, a true sphere, whereas the atmosphere and the hydrosphere are but spherical shells. The lithosphere is a nearly perfect oblate spheroid, with a polar diameter of 7899.7 miles and an equatorial diameter of 7926.5 miles. Its meridional circumference is 24,860 miles; its equatorial circumference, 24,902 miles. Its greatest elevation above sea level, Mt. Everest, is about half a mile less than the greatest depth of the sea.

The lithosphere falls naturally into two parts: the *terrestrial* portion and the *suboceanic* portion. The former is divided into the *continental platforms,* the latter into the *ocean basins.* The transition from the continental platforms to the ocean basins is not abrupt, but is bridged by a submerged border of the continental portions known as the *continental shelf.* This shelf slopes gently into the ocean basins from each continental segment until it is submerged to the depth of approximately six hundred feet, whence the descent into the abyssal depths is more abrupt. Recent work, however, has shown that the continental shelf does not in all cases give way to the ocean basins at the six-hundred-foot line. Johnson has lately demonstrated that the shore of New England presents many exceptions to the general rule.

Since the terrestrial portion of the lithosphere is the main seat of human activities, it is the part best known to geologists. Here it is that the geological agencies of destruction and reconstruction have left in the rocks a history which can be read. Many of the agencies which diversify the terrestrial landscape are prevented from attacking the suboceanic portion of the earth's surface because of the protective covering of water over the latter. The result is that while the suboceanic surface is rolling and is modified by volcanic peaks, it is not deeply dissected by the destructive processes characterizing the terrestrial surface. The tendency in the ocean bottoms is to flatness, because it is there that the waste material worn from the land is dumped. The tendency on land is also to flatness, but only after a cycle during which the topography is roughened. This cycle has never been completed, so that the land areas have never attained essential universal flatness; and, as we shall see later, probably they never will.

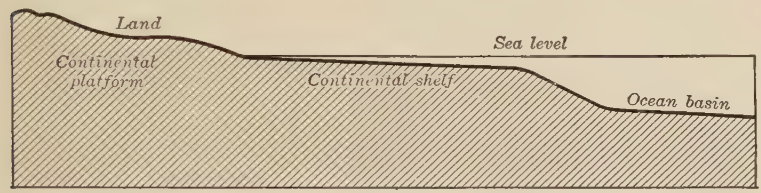

FIG. 13. Diagram showing the profile of the lithosphere from land to ocean basin

It is apparent that only a small portion of the lithosphere is available for direct study by the student of earth science. Less than 30 per cent of the total surface of the earth is occupied by land. Of the remainder, the part below the oceans, but little can be known directly. In the same way, that portion of the lithosphere which forms the great interior of the earth can be known only by inference. It can be seen that the geologist is handicapped in a way that the botanist and the zoölogist are not. The geologist finds much of the phenomena of his field completely hidden and unavailable for direct observation. Unlike the students of many other branches of natural science, he must resort to inference for many of the fundamental principles of his science, since the material with which he works is to a large extent either entirely unrecoverable or too large for isolation and detailed study. Under this handicap it is to the credit of those who built the study of the earth into a science that so much solid truth has been accumulated regarding its history and that of its inhabitants.

The topography of the earth's surface. *Continents and ocean basins.* If the rock material of the continental masses were smoothed out, so that all lands stood uniformly and evenly at the same height, the level above the surface of the sea would be close to 2300 feet. In the same way, if the ocean bottoms were brought to a common level, they would lie at something less than 13,000 feet below the surface of the sea. These figures are the average height and depth of the continental platforms and ocean basins, respectively, and together produce the major relief features of the globe. The average height of the lands and the average depth of the sea therefore show a difference in altitude of about 3 miles. The maximum relief, of course, would be much greater if Mt. Everest (about 29,000 feet) and the Nero Deep (about 32,000 feet) were compared. The difference here is between 11 and 12 miles. To human eyes this major relief of the earth's surface cannot help being impressive, and we shall presently see that the reason why the lands stand so high above the ocean basins is one of the largest of the still unsolved problems of geological science. It should be remembered, however, that 3 or even 12 miles is insignificant compared with the radius of the earth. In proportion the major relief features of the earth are of little more consequence than the irregularities on the surface of an eggshell.

The German geologist Penck has characterized the continental platforms as a mass roughly star-shaped surrounding the north pole and sending rays southward. These rays fall into two principal divisions: one comprising Eurasia, Africa, and Australia; the other, North and South America. The oceans, although bearing different names in different parts, are continuous about the irregular rays of the continental masses. The continents have also been described as roughly triangular in outline, with their broadest faces to the north and their apexes to the south. The ocean basins can be seen to fit around the continents, with their broad ends to the south and their apexes to the north. This relationship of land and ocean areas is marred by the shape and position of Australia and Antarctica. The fact of great significance in this connection is that the land masses peter out southward, whereas the oceanic areas diminish northward, so that the Northern Hemisphere contains most of the land, and the Southern Hemisphere most of the water.

Another interesting fact concerning the distribution of land and water on the globe is that the continents and ocean basins occupy antipodal positions. Directly opposite each continental land mass, on the other side of the globe, is an ocean basin or a portion of an ocean basin. Impressed by this reciprocal relationship between land and ocean areas, W. Lowthian Green prophesied the existence of a great continent over the south pole to balance the ocean basin known to be present over the north pole before the continent of Antarctica was discovered.

Origin of continents and ocean basins. Less than a hundred years ago it was the belief and teaching of many of the great geologists of the day that all the oceanic troughs had once been dry land. This belief, like so many others that develop in the early flush of youth in a rapidly growing science, is becoming discredited with the passage of time. Much evidence has been collected in the last century, and from this great accumulation little proof of the old idea can be culled. On the contrary, much evidence points to the essential permanency of the continents and ocean basins throughout at least all later geological time. While it is true that oceans tend to grow at the expense of the continents, there is no generally accepted evidence to prove that *complete interchange* of land and sea bottom has ever taken place. Tales of foundering continents are gradually being thrown into the scientific scrap-heap, and the doctrine of the essential permanency of continents and ocean basins is fast being fortified by an ever-enlarging bulwark of facts. The lines of evidence in support of this doctrine may be summarized as follows: (1) Although the sea has often encroached upon the land, the deposits laid down in these seas and their entombed plants and animals show that the waters were very shallow and in no sense comparable to the conditions in areas of deep sea. (2) If sections of the continents had at any past time been parts of the ocean basins, some record of deep-sea deposits should be available on land today. With a few slight exceptions, every attempt to find deposits of deep-sea origin on land has failed. (3) It is now generally believed that rock constituting the oceanic segments of the earth's crust is heavier than that in the continents. For this reason the heavy ocean basins have tended to sink from the beginning, and the lighter continental masses have tended to rise. If the major relief features of the globe are actually due to such differences in density, as seems likely, it is impossible to conceive of the continents sinking and the ocean basins rising.

Continental relief features. The lands of the continental platforms can be grouped broadly into (1) *mountains*, (2) *plateaus*, and (3) *plains*. In general, any land which stands conspicuously higher than its surroundings and has but slight area at its summit is called a *mountain*. Any relatively flat land of large area which stands conspicuously high is a *plateau*. All the rest of the continental lands which are more or less low are *plains*. These terms, based upon the altitude of land above sea level, must of necessity be loosely used, because the nature of land forms is such that one type may gradually and almost imperceptibly grade into another. A plateau may be so dissected that parts stand out as peaks with little summit area, and in a sense form mountains. In the same way plateaus grade into plains, so that in many cases it is not clear what term should be applied. The Great Plains of western North America are in places higher than the Appalachian Mountains of the East, and form a typical plateau, which, however, becomes lower and more plainlike to the east. Then, too, many isolated areas of land in low countries, although standing conspicuously above their surroundings and of slight summit area, are of too small a size to be classed with mountains. Such land forms are called *hills*. There is no exact line of demarcation between a hill and a mountain, inasmuch as the terms are differently applied in different regions. Some of the mountains of eastern North America would hardly be considered as such in the areas of very high land in the western part of that continent. Some attempt has been made to classify land forms according to their geological history and structure, but difficulties have arisen which confuse the issue rather than clarify it. The terms applied to land forms are of provincial origin, and to a great extent their meaning has remained so. After all, an exact distinction between mountains, plateaus, and plains is not necessary to a scientific understanding. As we shall see, the Great Sculptor of continents works with many and diverse tools, and the results of the work are nearly as variegated as the tools used in their production.

Rocks of the earth's crust. Rocks form the bones of the earth's body as well as its skin; that is, both the consolidated mineral material of the lithosphere and the unconsolidated surface soils, clays, sands, etc. are called *rocks*. Usually a rock is made up of various minerals heterogeneously mixed. Only exceptionally is a rock composed of a single mineral or does it possess definite chemical composition and structure throughout. Rocks differ endlessly in regard to such properties as color, hardness, strength, texture, chemical make-up, etc., but in regard to their origin and history they can be placed in one of three great groups. These groups, (1) *igneous rocks*, (2) *sedimentary rocks*, and (3) *metamorphic rocks*, are considered in detail in Chapter V.

Igneous rocks. "Igneous rocks," as the name implies, includes all rocks that were derived from hot material. The living volcanoes of the earth give us a picture of the original condition of all igneous rocks. In many regions today hot liquid rocks gush out of cracks in the earth's crust from unknown depths to solidify on the surface as lavas. Some of this hot material fails to reach the surface and solidifies at varying depths below. This igneous-rock material is the original and fundamental stuff out of which the earth was formed, and the other rock types are but minor derivatives. Igneous rocks of all types are solidified parts of a liquid mass, examples of which we can see issuing from volcanic vents. Any liquid mass of rock is called a *magma.* That part of a magma which reaches the surface before cooling enough to solidify forms rocks on the surface of the earth known as the *extrusive igneous rocks.* These rocks usually cool so rapidly that individual minerals have no time to form; as a result they are apt to be glassy or slaggy in texture. Magmas which solidify beneath the earth's surface form the *intrusive igneous rocks.* Because of slow cooling, this type usually has its mineral elements well crystallized, as can

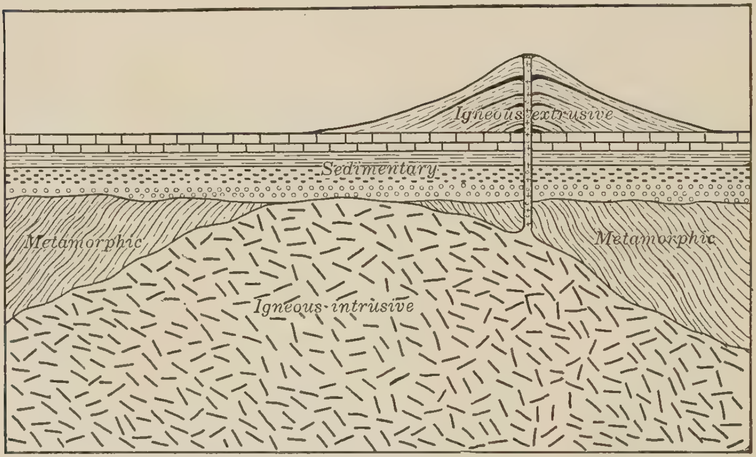

FIG. 14. Hypothetical diagram indicating the relationships of the main groups of rocks

be seen in a piece of granite, a rock of this group. Removal of the overlying material has brought intrusives to the surface in many regions.

Sedimentary rocks. When igneous rocks decay or are broken up by the agencies of weathering and erosion, the small pieces are often laid down again and cemented into new rocks. Everybody is familiar with mud, sand, and gravel, which rivers carry from the land to deposit in the lakes and sea. Here the materials form a *sediment*, and from this the sedimentary rocks are made. The grains of sedimentary rocks are always more or less rounded and are usually deposited under water. They are usually arranged in layers, and for this reason they are sometimes called *stratified rocks.* Because of their different origin igneous rocks are seldom stratified; they are often described as *massive.* Sedimentary rocks were originally derived from the igneous type, which is the mother of all things on earth, but they are often the direct result of the breaking down of earlier sedimentary and metamorphic rocks. Any material laid down as a sediment in the water or on the lands of the earth and later cemented into consolidated rock is a sedimentary rock. It is seen that sedimentary rocks are always secondary in origin and are usually transported bit by bit to their present location from some other locality.

Metamorphic rocks. Any rocks whose form has been changed at any time after their formation fall into the third great group, the metamorphic rocks. Thus it is possible to have rocks originally of the igneous or the sedimentary type changed into metamorphic rocks. Rocks are changed in form largely by (1) great pressure and (2) great heat or (3) by a combination of these. In some cases replacement of minerals with the aid of water is important in changing the nature of rock material. The study of the change of rocks from one type to another is one of the largest branches of geology. Many agencies are everywhere at work to alter the composition of all rocks, so that in a strict sense all rocks are to a greater or less degree metamorphic. The term is, however, ordinarily restricted to those rocks which have been changed significantly.

CHAPTER II

SURFACE PROCESSES OF DESTRUCTION

The conception of perpetual change in nature took form at an early date in the human mind. The first ideas of a world in constant flux were not based primarily on carefully observed fact and were not destined to take a firm and lasting hold on the minds of men. The natural instincts of man work to obliterate the belief in the impermanency of things because of fear of the unknown and because of the uncertainty which change brings. It was thus that the doctrine of evolution in plants and animals, although conceived at an early date, languished until the middle of the last century, when it fell like strong acid from the pen of Charles Darwin upon the reason of thinking men. Before this date it was thought that the great array of different plants and animals were brought forth by special and separate acts of creation, that each species remained fixed in form and habit from the beginning. The idea that all races of living things tend to change, that new forms develop and old ones disappear, that the entire assemblage of living creatures is woven together into a more or less closely knitted fabric, is daily being more firmly supported by a rapidly increasing body of facts.

For many years poets have sung of the "everlasting hills," of the permanency of their physical environment. With the progress of geological science it has become clear that nothing is more certain than that the hills are not everlasting, that the ebb and flow demonstrated so clearly for the races of plants and animals is true of their physical environment as well. Nothing is clearer than that some day the highest mountain peak will crumble and fall away, perhaps to rise again at a later date. Whole mountain ranges are known to have been built and removed within but a small fraction of geological time. As it is with the mountains, so it is with many other features of the face of the earth. Nothing endures; the earth as we know it today was very different yesterday, and will be very different tomorrow. With the refinement of modern methods of research, a great deal is being learned about the basic units of matter. The molecule and atom no longer suffice as the units of matter; still smaller divisions have been clearly demonstrated. For a long time it was thought that the chemical elements were of definite and constant molecular make-up, but that nicety and precision which have been able to measure the charge of electricity on a fraction of an atom have shown even the molecules of various chemical elements to be unstable. Thus we see that alike in the living and in the inanimate, in the inconceivably large and in the infinitesimally small, constant change is the normal condition.

The earth planet as we see it today presents to the trained eye such a changing panorama. A long and complicated history lies behind both the large and the small features of our globe. Not only the mountain range as a whole but the individual rock masses which comprise it have gone through many and diverse changes; great bodies of sea water as well as the particles of which they are composed tell stories of endless variation. The geologist attempts to read these stories and from them to build up a complete history of the earth. Let us see how far he has been successful in this undertaking.

WEATHERING

The atmosphere works in various ways to destroy the form of the lands. The result of all processes whereby atmospheric agencies loosen, break, or decompose rock material is called *weathering*. The weapons of the atmosphere are two-edged swords; on one side they work mechanically, and on the other side chemically. The attack upon the land is endless, but varies in intensity from place to place and from time to time. Slowly but surely the consolidated rock material exposed to the atmosphere is ground, shattered, or rotted into loose rock and soil, which covers the continents as a mantle and is known as the *mantle rock.*

MECHANICAL AGENCIES

Rain. The impact of rain on the earth's crust seems of slight importance in the destruction of hard rock substance. The effect of a single rainstorm may be exceedingly slight, and the result of many may be hardly noticeable. On the other hand, if almost limitless time be allowed, startling results can be and are produced by the impact of rain on the land. It is so with most geological processes. Great results are attained through the repeated action of seemingly unimportant agencies acting over inconceivably long periods of time. Although some agencies act faster than others, the element of time is important in all geological equations.

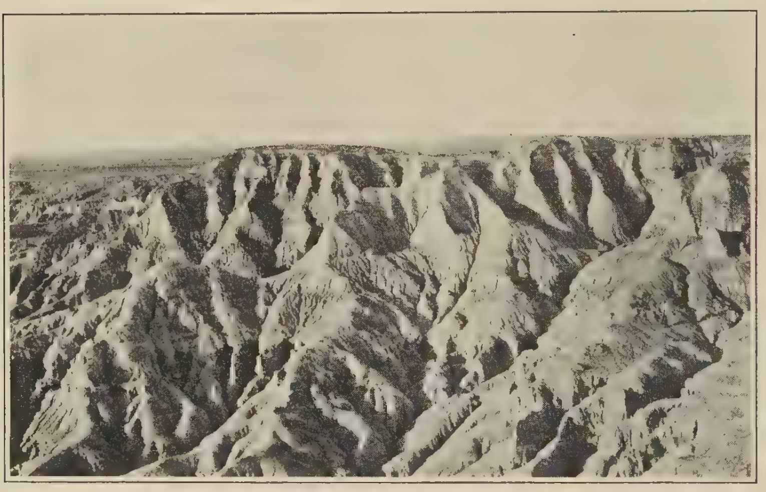

FIG. 15. Bad Lands, Nebraska. (Photograph by N. H. Darton. Courtesy of the United States Geological Survey)

The result of torrential rains working on weak sedimentary rocks

An exception to this general rule is found in the entirely unusual storm, which through its intensity may effect more geological work in a particular locality than countless rains of milder disposition. Such extreme storms may come to any single region but once in several centuries, yet their destructive power must be of greater significance than is commonly recognized.

The mechanical work of rain is most effective in the loose material constituting the mantle rock. It tends (1) to lubricate unconsolidated material and cause soil on slopes to creep downhill; (2) to wash dust out of the atmosphere and deposit it on the earth's surface; (3) to soften hard rocks by working into their pore space; (4) to remove the finer material of soils, leaving the coarser behind. It is hard to divorce the action of rain from that of running water, and it should be remembered that many geological processes work together and are mutually interdependent. In the same way, a geological agent may act both chemically and mechanically, as is the case with the softening effect of rain on consolidated rock material. In

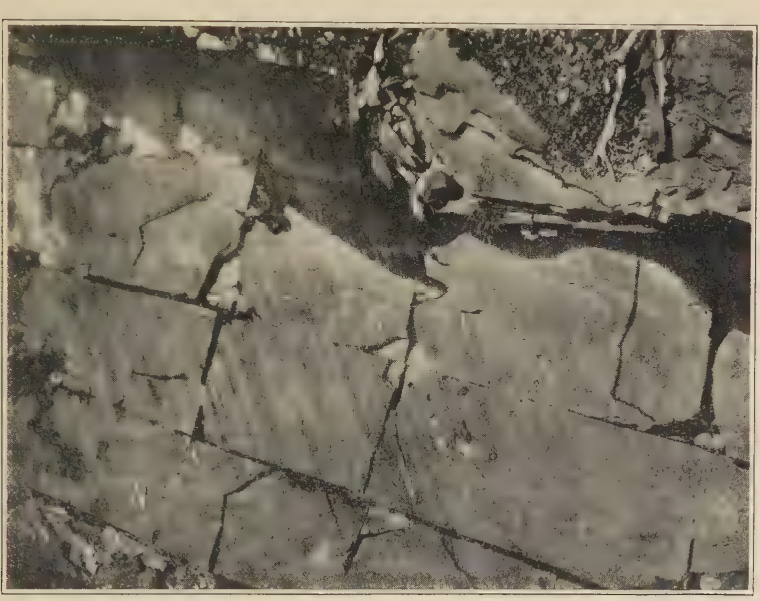

FIG. 16. Joints in sedimentary rock. (Courtesy of the United States Geological Survey)

untangling the jumble of processes found in nature and categorizing them it is necessary to emphasize their most marked peculiarities, but unfortunately such a proceeding may obscure some of the less important characteristics. Rain works fundamentally as a mechanical agent of destruction, but occasionally, as noted above, it works chemically, and in a sense even constructively, as in the case of a slight building up of the lands effected by the deposition of atmospheric dust.

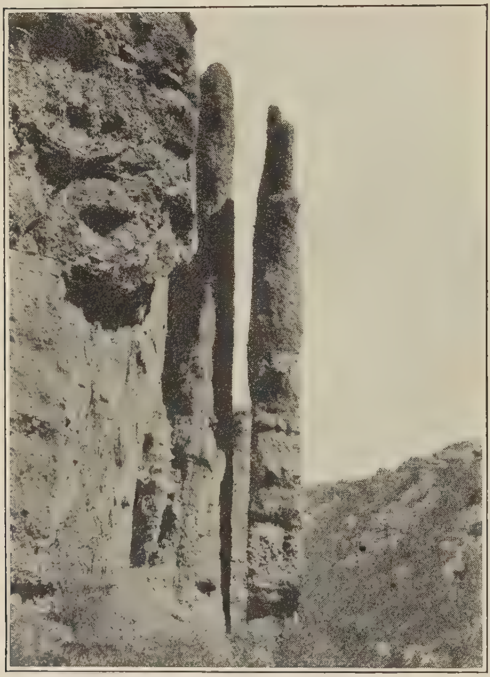

FIG. 17. Isolation of a rock chimney in Wyoming by weathering along a joint in volcanic rocks

Frost. All materials suffer a change upon freezing; most contract, a few expand. Water belongs to the latter, much smaller group, and its expansion upon freezing increases its bulk about one tenth. If water in a confined vessel is frozen solid, the great power generated by its expansion can be observed. Everybody knows how easily the water in the radiator of an automobile shatters its metal receptacle when it freezes solid. The pressure developed by freezing water is more than two thousand pounds per square inch, a force which can seldom be resisted.

No rock body forms a continuous sheet of undivided material, not even the massive igneous rocks. All rocks are divided by planes which separate the mass into blocks of various sizes and shapes. Such planes of division are called *joints.*

Along joints and in the pores and fissures of rocks rain water tends to accumulate. Continual freezing, melting, and refreezing of this water slowly breaks the rock to bits. Not only are the larger blocks slowly wedged apart along joint planes, but each block, through the repeated freezing of the water within its pores, grows weaker and gradually disintegrates.

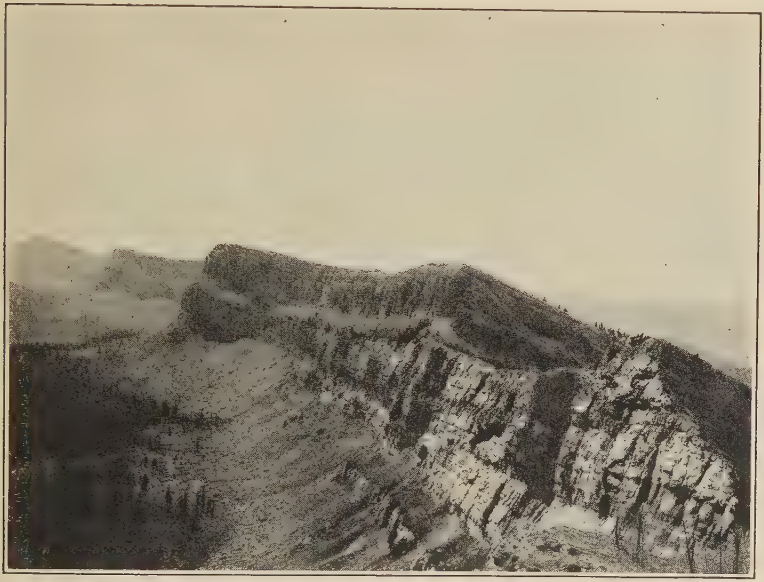

FIG. 18. Talus deposited at the base of a limestone cliff in Montana. (Courtesy of Dr. J. E. Kirkwood)

On all high mountains, where the protective mantle of soil and vegetation is absent, the action of frost has produced a desolate waste of broken rock fragments. In a surprisingly short time tombstones and monuments become scarred by frost. Everywhere in regions of cold winters, frost is of great importance in shattering rocks. In tropical regions of low altitude the destructive action of freezing water is, of course, practically absent.

The work of frost is most conspicuously seen on cliffs. Frost working on a steep slope loosens blocks of rock of various sizes.

Gravity carries such fragments downward to the base of the declivity to places where the slope is too gentle to allow the pieces to roll farther. Here they accumulate to form the deposit known as *talus* (Fig. 18). All cliffs in regions where the winter is severe are draped with such talus material. The slope at which talus lies is determined by the size and shape of the fragments, large irregular pieces lying at a steeper angle than small uniform pieces. When loose material of any type comes to rest on a slope, the angle of slope is called the *angle of rest*. This angle is seldom less than 25 degrees in talus deposits and may be as high as 45 degrees. Since talus deposits normally flare out at their bases and thin out at their edges, giving the appearance of a half cone with its apex well up on the side and its base at the foot of the cliff, a single talus accumulation is sometimes called a *talus cone*. (See Fig. 19.) The steepness of cliffs, as well as their height, is reduced by frost action.

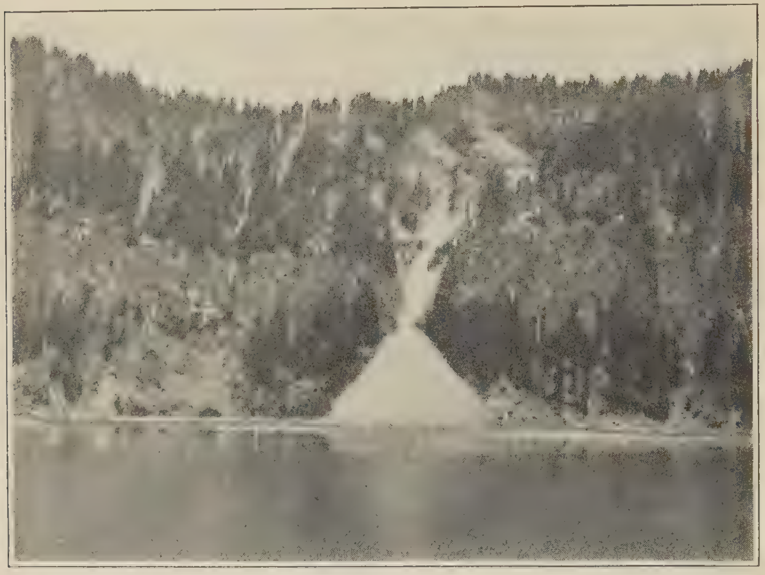

FIG. 19. A talus cone, "The Wineglass," rim of Crater Lake, Oregon

By alternate freezing and thawing, soil and loose rocky material are sometimes made to creep down slopes. In moist regions of severe climate such slowly moving material may attain to hundreds of feet in length. If the fragments are of the nature of talus, the moving mass is called a *rock glacier*; if the material is of the nature of soil, the moving mass is called a *soil creep*. Soil creep is distinguished from *landslide* in that movement is slow in the former and rapid in the latter. Soil creeps are induced entirely through the mechanical action of frost, whereas landslides are brought about by other causes, as we shall see later.

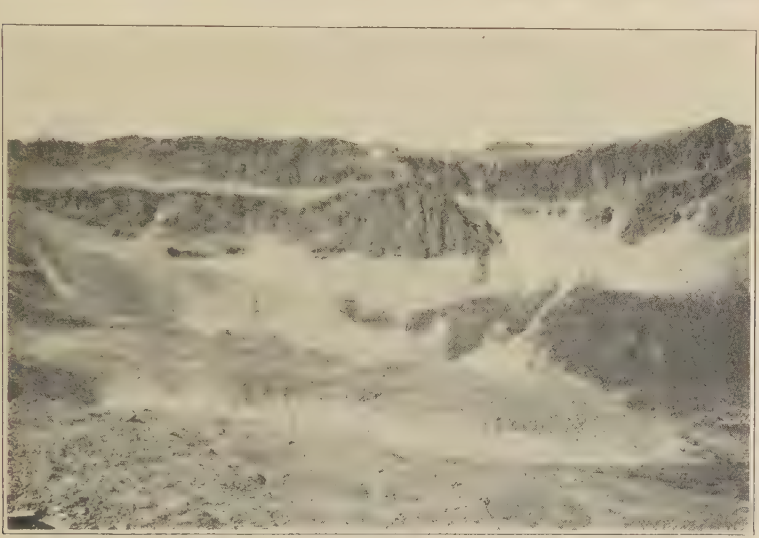

FIG. 20. A rock glacier in Colorado. (Courtesy of the United States Geological Survey)

Alternate freezing and thawing of the water associated with the rock fragments have caused this mass of talus to move slowly and to assume the appearance of a glacier

Although frost is a powerful agent of destruction, it works in a very superficial zone. In most places rocks a few feet below the surface are free from its blasting effects. Like other agencies dependent upon water for their existence, frost is of importance only in regions of rather moist climate and abundant rainfall, and even in such favored places frost action is not conspicuous unless alternate freezing and thawing are permitted by a sufficient range in temperature variation. For this reason the work of frost is unimportant or absent in the polar regions, where the ground is permanently frozen, as well as in low tropical countries, where freezing is unknown.

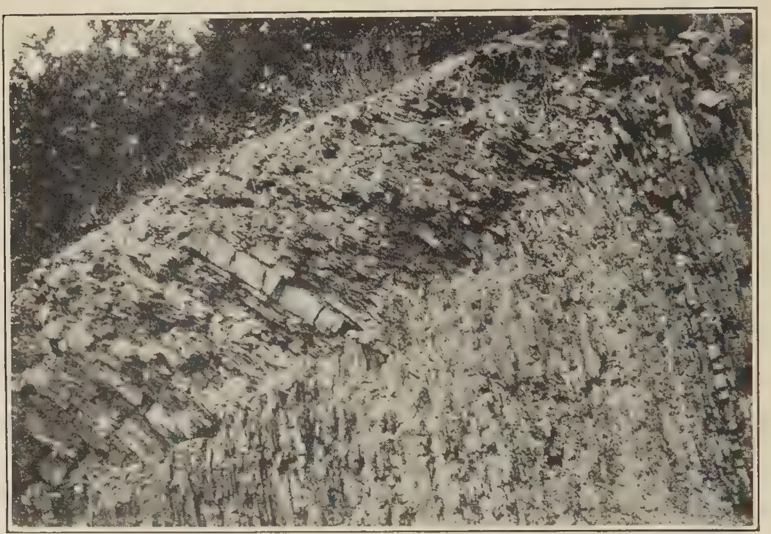

FIG. 21. Rock creep. (Courtesy of the United States Geological Survey)

The shales have crept downhill as a result of frost action aided by gravity

Daily changes in temperature. The atmosphere has an effective means of destroying rock surfaces in regions where rainfall is slight and the climate mild. In desert regions, where the air is dry and clear, radiation of heat is rapid. In such places little vegetation protects the surface of the land, so that the scorching blaze of the sun heats the naked rocks to a high temperature during the day, the outside of the rocks heating and expanding more rapidly than the interior. At night the heat is rapidly lost by radiation, so that the surface cools and contracts more rapidly than the interior. Thus strains are set up which cause the rock to break into fragments, In this way accumulations of rock débris similar in aspect to the frost-formed talus of moist regions may form at the base of cliffs in desert areas. In the Sahara Desert, at sunrise and sundown, in the cool of early morning and evening, rocks breaking in this manner can be heard to crack with rifle-like reports. The same phenomenon can be observed in many semiarid mountain regions, notably in the Rocky Mountains.

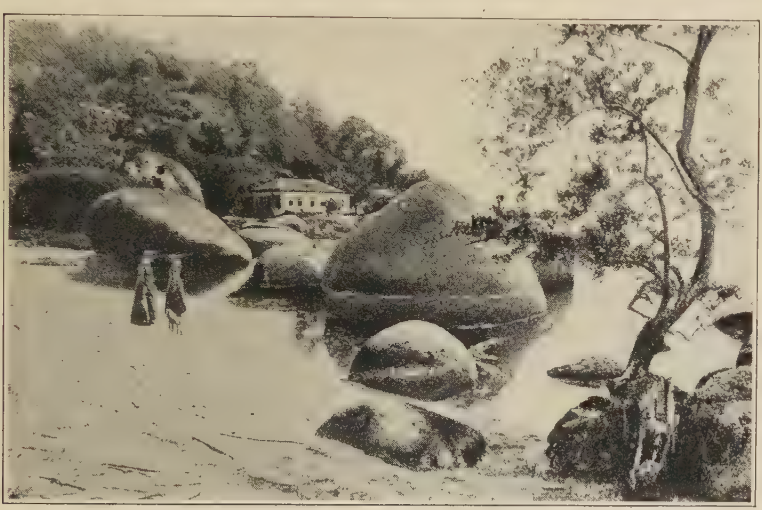

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FIG. 22. Bowlders in Brazil produced by exfoliation. (Photograph by J. C. Branner)

Many rocks under such extremes of temperature changes tend to lose their surface portions. Layers very much like the concentric spheres of an onion are formed and broken off by the alternate expansion and contraction of the rock (Fig. 23). This process, known as *exfoliation*, gives smooth, rounded faces to all rocks so affected, regardless of their composition. Many of the striking rock domes, such as Stone Mountain near Atlanta, Georgia, were sculptured in this way. Exfoliation, while most important in desert countries, is to be observed in nearly every place where rock surfaces are exposed to the direct rays of the sun. Like frost action, exfoliation is active over a very superficial zone at the earth's surface.

The power of conducting heat is so low in rocks that those but a few inches below the surface are unaltered by this process.

Wind. Most people live in temperate regions of plentiful rainfall and have no idea of the colossal work accomplished by wind. Only where rainfall is slight and vegetation scarce can the wind do its most effective work. On the broad open waste spaces of the earth the inquisitive traveler sees the real potency of moving air as a geological agent.

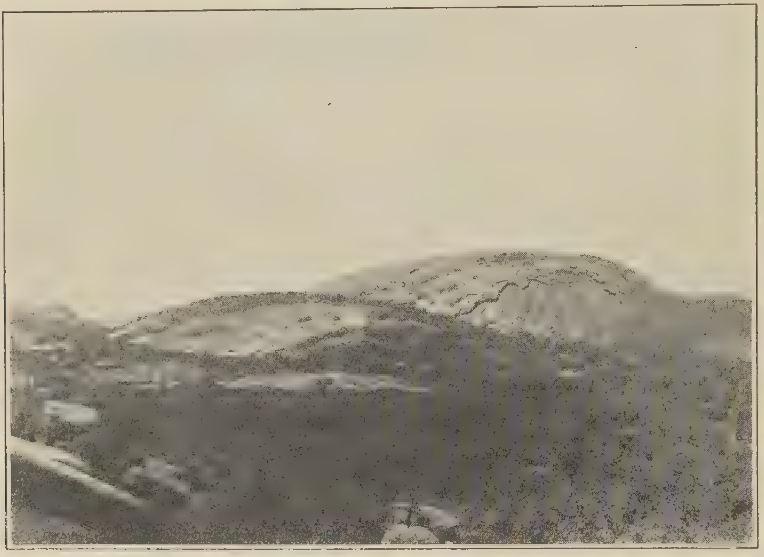

FIG. 23. A rock dome in Texas showing exfoliation on a large scale. (Courtesy of the United States Geological Survey)

Wind blowing over soil securely anchored by vegetation does little work, since sand, the effective tool of wind erosion, is lacking. Clean air moving rapidly can actually carry loose rocks down inclines and can uproot trees, but such activity of the wind is of local extent and minor importance. The frightful havoc occasionally done by wind moving in tornadoes is frequently emphasized in current literature, whereas the slow but constant destruction of the earth's surface by wind-blown sand is apt to be overlooked. Wind destroys land surfaces mainly in two ways:

1. Loose material produced in any way whatsoever by the weathering of rock is greedily snatched up by the moving air and is carried along, perhaps to be dropped later in some place remote from its source. The stronger the wind, the larger the bits of rock waste it is able to carry. Like a puppy at play, the wind is whimsical. Steady winds may carry fine sand and dust for great distances. Puffy winds may alternately carry and drop their burden of loose material. Swirling winds may drift soil particles, even as snow is piled up, very near the place whence the material was derived. Pits (*blow-outs*) may be excavated in light soil that is but sparsely covered with vegetation. The "dry" farmer of the Western plains knows and dislikes the wind, which dries up his land, removes his soil, and may even run away with his crop of grain before it has become firmly rooted. Winds are assiduously picking up loose material and rolling along particles too large to lift bodily. Such work by wind is called *deflation*.

2. The materials carried by the wind, though gathered willy-nilly, are almost always present in greater or less degree. The pockets of the wind, like those of a small boy, are filled with a variety of things. Fine particles of earthy matter are most common; but pollen of flowers, spores of plants, and animal organisms of almost microscopic minuteness are there. Even small amounts of dust dropped into the atmosphere from outer space are caught up by the wind. Material disgorged from the interior of the earth through the mouths of volcanoes, and shattered into fine bits by explosive eruption, is carried by the wind. In 1883 the volcano of Krakatoa in the East Indies blew its head off with such violence that great clouds of dust were projected high into the air. By studying the sunsets, which were peculiarly affected by this dust, it was ascertained that in about fifteen days planetary and other winds had carried matter erupted from Krakatoa completely round the world. Mountain climbers detected it on the snows of high peaks, and arctic explorers found it on the ice of the Far

North. Gradually this dust settled out of the air; it was not until three years after the eruption, and after some of it had very likely circled about the earth several times, that the dust ejected in this single eruption left the atmosphere. Such material is exceedingly fine and light, so that even the gentlest breezes can carry it. Only strong winds can carry the larger sand grains, which are the major tools of wind destruction.

Dust and sand when blown against a rock surface wear away both hard and soft rocks. If the rock is composed of minerals varying in hardness, a picturesque fretwork of ridges and hollows may be formed. If a pebble in the desert is for a long time exposed to such a sand blast, the surface exposed to the prevailing wind will be planed. If the pebble is turned by a strong gust of wind, a new surface will be exposed and planed. Pebbles faceted in this way are common in desert regions, and go by the names of *einkanter*, *dreikanter*, etc., depending upon the number of faces so developed (Fig. 24).

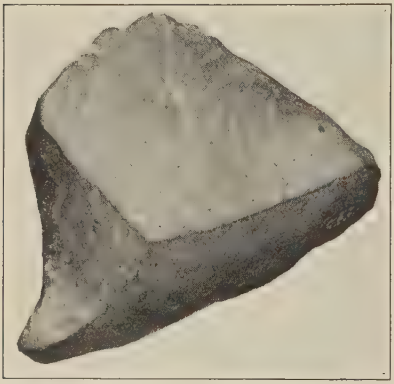

FIG. 24. A wind-carved pebble (dreikanter). (Courtesy of the United States Geological Survey)

In a larger way, whole surfaces of rock material may be pulverized and carried away by the wind. Since most rocks vary in hardness, it is not uncommon in desert countries to see the tougher remnants of a formerly extensive formation standing in isolation as hillocks, often picturesquely carved by the sand blasts. Many of the fantastic rock structures which charm the eye of the traveler in western North America — notably those to be seen in the Garden of the Gods in Colorado — were produced largely through the action of wind-blown sand. Such wearing away of rock by sand blown against its surface is called *abrasion*.

Lightning. The disastrous effect of lightning, which at times strikes man and his dwelling, is well known. The fact that rocks are sometimes shattered on a large scale by lightning is not so generally known. When it strikes soil of a sandy texture, the heat generated is sometimes sufficient to fuse the loose particles into irregular rods and tubes known as *fulgurites*.

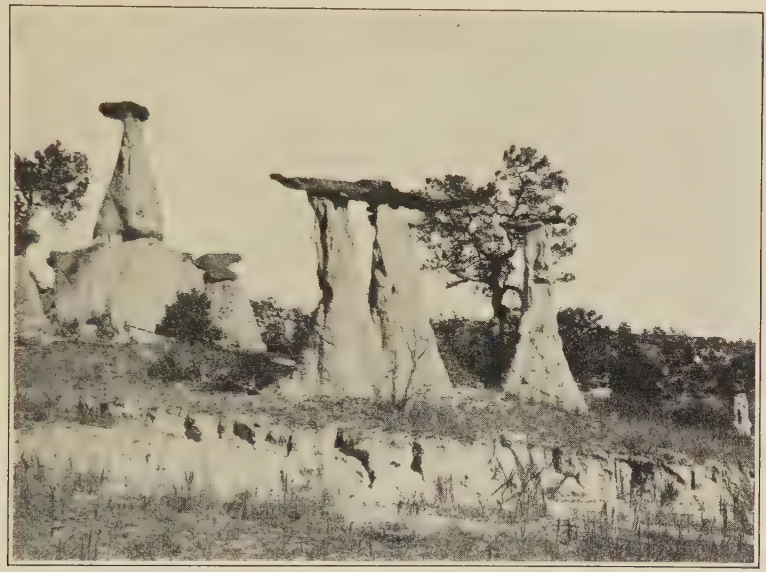

FIG. 25. Freaks of erosion in Monument Park, Colorado. (Courtesy of the United States Geological Survey)

Note the effect of variation in hardness upon the shape of the pedestals

Some mountain tops have been cracked and riddled in this way, but the effects of lightning are on the whole more spectacular than important.

CHEMICAL AGENCIES

Quite distinct from the brute force of the mechanical instruments used by the atmosphere to destroy the lithosphere is the insidious action of the chemical substances in air. Dry air, such as that over the Sahara Desert, has little direct power to destroy things chemically, as is shown by the well-preserved mummies of ancient Egyptians uncovered after several thousands of years of burial. Rocks, which are far more resistant to decay than is the flimsy substance of the human body, are practically untouched by chemical weathering under a dry atmosphere. Where the atmosphere is moist, however, the story is very different. Nothing can resist the cankerous activity of moist air. Carbon dioxide and oxygen, the two most active gases in the atmosphere, are the instruments of chemical destruction, and work effectively only when they are dissolved in water.

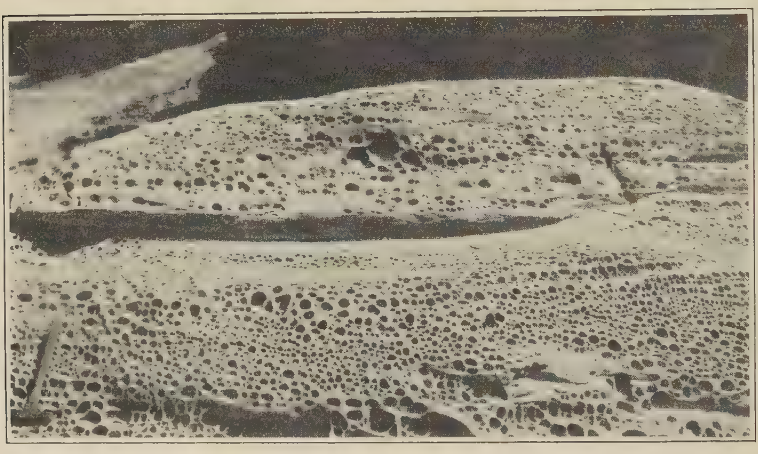

FIG. 26. Solution weathering in sandstone, Utah. (Photograph by D. J. Fisher. Courtesy of the United States Geological Survey)

Solution. Rain water descending upon the lands is charged with carbon dioxide and oxygen captured from the air, and as it works its way into the soil, more is obtained from decayed plants and animals. Water thus charged effects a slow decomposition in the rock material it touches. The breaking down of a rock is a complex process and is usually consummated through a combination of mechanical and chemical forces. All rocks are open to the disruptive effects of frost, the blasting by wind-blown sand, the pulverizing effect of running

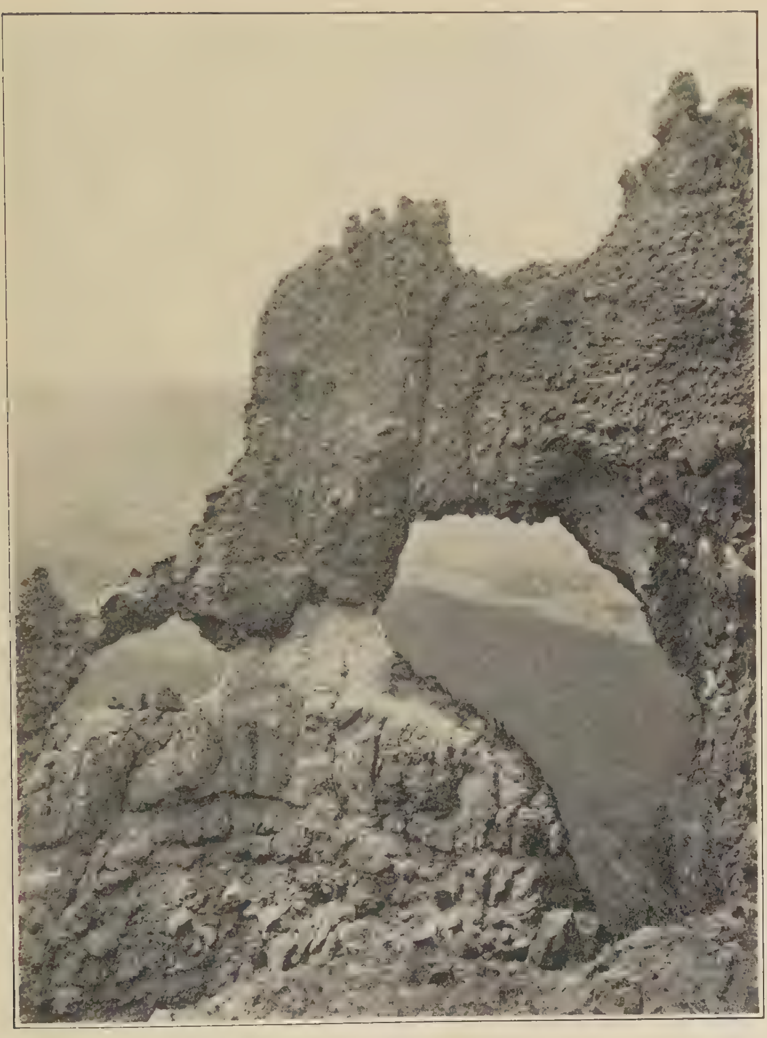

FIG. 27. Differential weathering. (Photograph by K. D. Swan. Courtesy of the United States Forest Service)

A combination of agencies attacking rocks of different texture and strength produce forms of striking appearance in many regions water and moving snow and ice, and the pounding of waves on shores. Such physical attack presents ever-freshened surfaces to the less conspicuous, but none the less gluttonous, assault of chemical agencies. Nearly all minerals are attacked and slowly digested by waters bearing oxygen and carbon dioxide. Some rocks whose constituent minerals yield readily to the attack are easily and in a relatively short time dissolved by such charged waters; other rocks whose minerals are more refractory to solution are but slowly eaten away. We have seen how the ground water is only a superficial film in the outer crust of the earth, largely because the pores and fissures in rocks become smaller and fewer with depth. Therefore it is apparent that solution, like other agents of weathering, cannot destroy the rocks at any great distance below the surface.

Oxidation. Oxygen is indispensable to the life functions of animals and many plants. While no such need is felt by inorganic matter, there are, nevertheless, many minerals which greedily absorb oxygen when opportunity is presented. When oxygen is absorbed by rocks containing such oxygen-starved minerals, the nature of the rocks is profoundly changed and new compounds are formed. This change, known as *oxidation,* is conspicuously demonstrated by the compounds of iron. On absorbing oxygen such compounds change from a dull gray, green, or bluish tint to a striking red color. If water is absorbed with the oxygen, rocks of a brown or yellow color result. Iron in some form is a mineral coloring pigment in nearly all rocks, but becomes such only after oxidation has taken place. It is quite logical to suppose that after a mineral has been oxidized, the resulting compound will be of greater volume than the original mineral. Such is actually the case. The newly formed substance is almost certain to be bulky, and while forming tends to pry apart the surrounding rocks. In this way rocks near the surface become disrupted and consequently weakened. The minerals resulting from oxidation likewise are apt to be weak and to resist poorly the onslaught of the many agencies of destruction.

Hydration. While some minerals are oxygen-starved, others are inordinately thirsty and absorb water at every opportunity. After such minerals have assimilated as much water as they can, they are said to be *hydrated.* As a log long submerged in water slowly absorbs some of the water into its pores and becomes bloated and heavy, so do minerals increase in volume under hydration. This increase in volume aids the slow destruction of the upper film of the earth's crust.

Carbonation. The carbon-dioxide content of rain water percolating through soil and insinuating itself into the nooks and crannies of rocks has a particular affinity for such chemical elements as sodium, calcium, iron, magnesium, and potash. Many of the rocks forming the framework of the earth are rich in these elements, so that although they are fairly resistant to other agencies of destruction, they are slowly disintegrated by the attack of carbonated waters. By carbonation, rocks which were originally complex and insoluble are broken down into soluble minerals of simpler molecular construction. Sometimes when carbon dioxide unites with a complex rock an increase in volume results, with the attendant disruption as in the case of oxidation and hydration. Carbonation aids in rock decay (1) by developing minerals which are easily attacked by solution and (2) by causing volumetric changes in rocks which undermine them and further their disintegration.

RUNNING WATER

Rainfall the ultimate source of all rivers. We have seen how some of the rain falling on the earth joins the ocean directly, some sinks into the porous cover of mantle rock to join the silent stream of underground water which flows by devious paths but in the end reaches the ocean, some is returned very soon to the atmosphere by evaporation, and some flows over the surface of the land to lakes and the sea in rivers. Sir John Murray estimated that 29,350 cubic miles of rain water falls upon the globe each year. This enormous amount of water is not equally distributed over the earth's surface, because of variation in the nature of winds in different latitudes and over lands of different altitude and topography. Although some regions receive so little rainfall as to be classified as arid or semiarid, even in such areas there is in most cases enough moisture not only to satisfy the thirsting of the soil and the atmosphere but also to furnish sufficient excess for the formation of rivers. The rain water which neither sinks into the soil nor returns to the atmosphere by evaporation is called the *run-off* and is that portion of the hydrosphere which makes streams possible and the varied scenic effects which streams produce on land areas. In regions drained by large rivers the run-off may be as high as 25 per cent of the total rainfall, as is the case in the basin of the Mississippi River.

This excess of rain water running over the lands in streams is of primary importance among destructive surface agencies. No other geological phenomenon is more conspicuous than work of rivers, and none is more important to man. Man's earthly destiny is greatly influenced by rivers; they cut channels through mountainous regions, making transcontinental railways possible; they furnish means of transportation and water for irrigation; they supply cheap mechanical and electrical power. For these blessings rivers exact their toll from mankind. All rivers are ungovernable. Despite the millions of dollars spent by the government of the United States to keep the Mississippi River within its banks, that perverse stream is little nearer to being satisfactorily controlled than in the days before the coming of the white man. Disastrous floods which destroy both life and property are nearly an annual occurrence along the lower reaches of the Mississippi. Similar havoc is wrought by all the other great rivers of the world.

Erosion by rivers. Whereas the weathering of the land by atmospheric agencies takes place everywhere, the destructive action of streams is concentrated in the immediate vicinity of their courses. For this reason stream erosion is more conspicuous than rock weathering, although the aggregate effect of the latter is probably greater. In studying the destructive action of geological agencies we shall use the term *erosion* in a broad sense to refer to the combined mechanical and chemical powers which break down and transport rock material.

It is perfectly clear that rain water cannot flow over the surface of the land unless the surface has a slope. It is equally clear that if the surface is perfectly smooth and even the run-off will be distributed evenly in a sheet. While the run-off is in rare cases sheetlike on some slopes, most slopes have slight depressions in which the excess rain water soon finds its way in small rills and rivulets to lower levels. In this way the water finally reaches a valley where water flows permanently. Small rills unite to form larger streams, which in turn form rivers in the steady march seaward.

All rivers carry mud, sand, and gravel, fed to them by the various agencies of weathering along their valley sides and broken loose by the wear of the water itself. Added to this mechanical burden of sediments of all varieties, rivers dissolve salts of many kinds from the rocks and soils of the regions they traverse. The dual mechanical and chemical work accomplished by the processes of weathering is likewise effected by all streams, but the mechanical work is always much greater than the chemical.

Three distinct processes are involved in river erosion: (1) The breaking-down process of *weathering* along the sides of river valleys feeds the streams vast quantities of material, from finely divided particles of soil through sand and gravel to large blocks of rock. This the streams receive through no effort of their own. (2) *Transportation*, the second process, takes place as soon as rivers have received such material from the agencies of weathering as can be transported. The power of streams to carry rock débris is definitely limited by the volume of their waters and the rate at which the waters flow. A small stream with low velocity cannot ordinarily move large bowlders, although it may spasmodically acquire great power to carry its burden during a spring freshet, and later lapse into relative impotence. The velocity of a stream is the immediate source of its power to transport, and is controlled by the degree of slope of the stream bed (*gradient*) and the amount of water. (3) *Corrasion*, the third process, is the wear on the rocks of a stream's channel caused by the movement of the water. An example of corrasion can be seen on almost any river bank, where the pebbles, gravel, and sand are apt to be rounded. These materials, contributed to the stream by processes of weathering, were originally rough and angular. In being moved by the stream the stones and small rock particles were buffeted one against another, and many against the rocks in the bottom of the stream channel. By this impact irregularities were worn away, and each individual stone or particle was gradually reduced to a smoother and rounder condition. Such wear naturally goes on more rapidly with softer rocks than with harder, and is more conspicuous in rocks the longer they are carried by the stream. Sand, silt, and mud are by-products of corrasion. In the buffeting process small pieces are worn from larger rocks, both those moving in the stream and those that are stationary in its bed and sides. The tendency of every stream is to break down its rough, unassorted burden into finer and smoother particles. This process is never completed, because the agencies of weathering are forever supplying new raw material.

Tools of river wear. Besides pulverizing the materials they carry, streams also gnaw away the sides of their channels. It is a significant fact that pure water moving over a rock surface has almost no power of mechanical destruction. To be able to corrade its channel a river must possess sand or silt, developed in its own body by grinding its load or picked up where its way leads through loose material, such as soil. Only at times when the river can hurl these small particles against its confining walls is its channel effectively widened or deepened. The sediment moved by a stream is in part carried in suspension and in part rolled along the bottom. Normally only the finer mud and silt travel in suspension, but at times, during flood, the sand and gravel which usually creep along the bottom are raised to a higher level in the stream and hurled against the confining banks. At the same time large bowlders, in some cases of unbelievable size, are rolled along the river bed. The North Fork of the Shoshone River in northwestern Wyoming becomes a raging torrent with the thaws and freshets of spring, so that large stones are bumped and rolled downstream. The steep slope of the channel aids the infuriated rush of the swollen waters, so that not uncommonly the dull thud of bowlders moving in the stream can be heard above the boom of the water. In almost all streams there are enormous bowlders which remain apparently undisturbed for years; but as certainly as they have been brought to their present positions by an extraordinary flood, just as certainly will an extraordinary flood carry them on downstream. It is obvious that when streams are swollen with the melting snows of winter and are rushing madly to the sea, they are able to carry heavier material, to carry more of it, and to carry it at a greater velocity. At such times corrasion is at its peak and, after countless repeated springs, produces the striking examples of river erosion to be seen in all lands.

Destructive effects of river work. Many factors influence the rate at which streams wear down their valleys, as well as the effect streams have on the appearance of the regions through which they flow. If a stream flows over a steep surface, the resultant erosion is great, both in the channel of the stream and in the general basin which the stream drains. Climatic conditions, particularly temperature and moisture, greatly influence erosion by rivers and the appearance of the result. Erosion in semiarid regions differs from that in places of abundant rainfall. In dry regions there is less rock decay than where the climate is humid, with the result that the harder, more resistant rocks of dry countries maintain to a large extent their predestined prominence. The contrary is true in moist areas: more valleys are excavated by streams, and the topography developed is apt to be smoother than that of semiarid regions. Mechanical destruction is more effective in dry lands than in lands that are moist, largely because the former lack the thick protective mantle of vegetation possessed by the latter. The result is that in arid and semiarid regions the features of the face of the earth are coarse, whereas in more humid regions they are more finely chiseled. The physical and chemical make-up of rocks and their geological arrangement strongly influence the rate at which they can be destroyed by erosion and help to determine their effect on the landscape. One of the most important controls over river erosion is the different hardness of the rocks over which the stream flows. If a stream flows over a steep gradient and encounters alternately hard and soft layers of rock, *rapids* may develop where the water flows over the resistant rock. Such rapids increase the velocity of the stream and hence the erosion, so that the water may cease to flow along its bed and fall over the hard ledge in a *waterfall* (Fig. 29). If a stream crosses highly inclined layers of different hardness, its valley is apt to be narrowed where the harder layers are crossed. Such a constriction is called

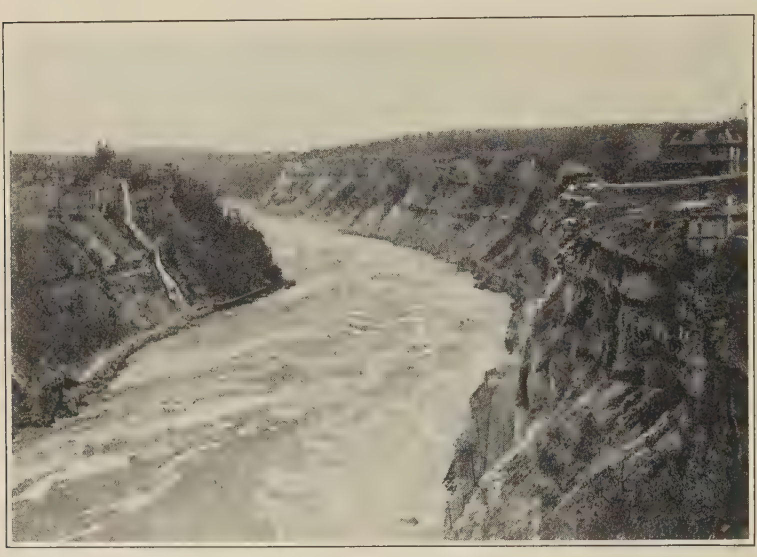

FIG. 28. Whirlpool Rapids, below Niagara Falls, New York. (Courtesy of the United States Geological Survey)

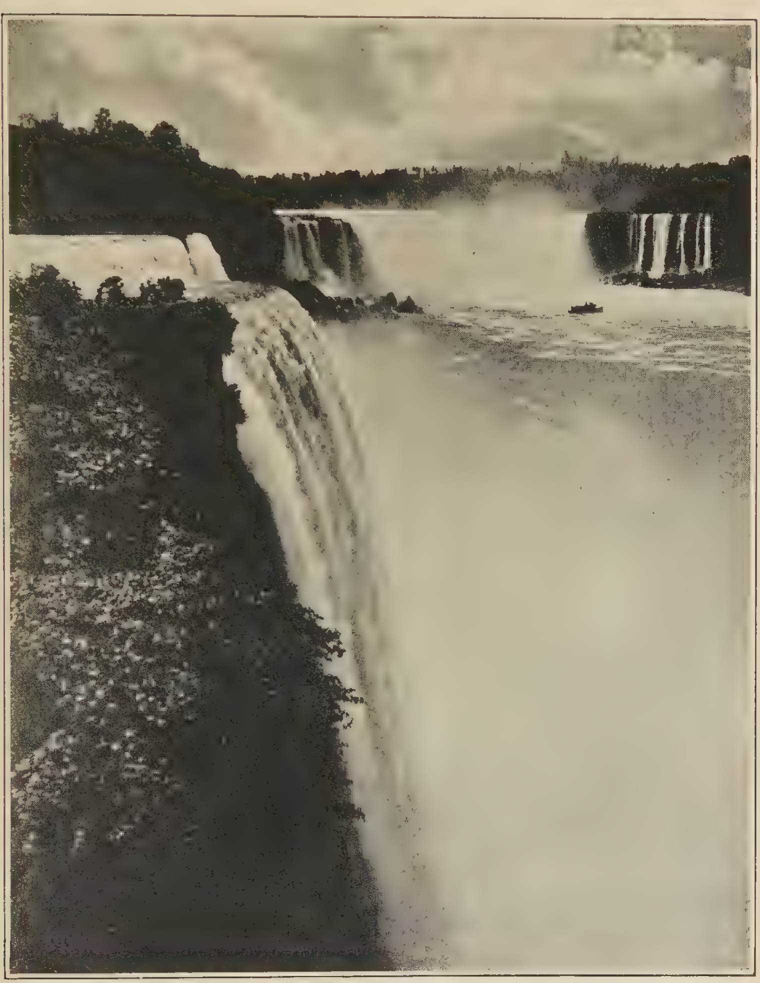

FIG. 29. Niagara, Queen of North American Falls. (Courtesy of the United States Geological Survey)

a *water gap* or *narrows*. In some regions of tilted sedimentary rocks the softer beds are removed by erosion, leaving the harder layers projecting above the general level in ridges known as *hogbacks* (Fig. 30). If an unusually hard layer of rock outcrops in the sides of a stream valley, the slopes of the valley tend to become gentle above the resistant layer and abrupt below it. Such a shelf of hard rock is known as a *rock terrace* (see frontispiece).

An interesting but minor effect of river erosion can be seen in the beds of many rivers whose waters flow rapidly and over pronounced irregularities. Such streams are characterized by eddies in which the water swirls in a circular course, carrying sand, silt, and pebbles which bore down into the bedrock, grinding out circular holes. Such excavations, called *potholes*, are often found on land surfaces no longer tenanted by streams (Fig. 31).

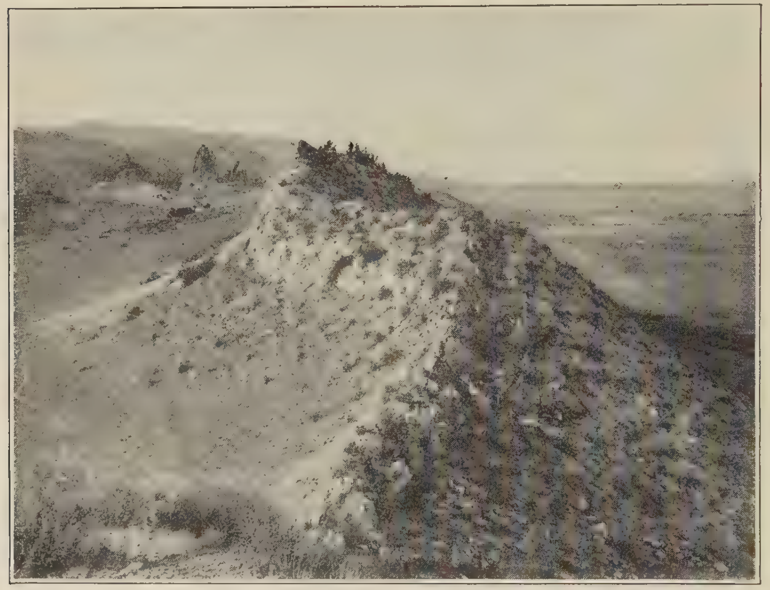

FIG. 30. A hogback in Colorado. (Courtesy of the United States Geological Survey)

When potholes are found in such places, they give clear evidence of the former existence of a vigorous stream. They are frequently associated with glacial streams; when they are found in a region no longer bearing glaciers or glacial rivers, the surrounding country must be studied before the true nature of the stream in which the potholes were formed can be understood. Potholes made by former glacial streams can ordinarily be distinguished by the associated destructive effects of the mother glaciers upon their valleys. These effects are so different from those produced by rivers that the two can hardly be confused. These and many other effects of river erosion are common and easily recognized by the general student; their interpretation in connection with the geologic history of a particular region may be complicated and can be made only through the careful observations of a trained specialist.

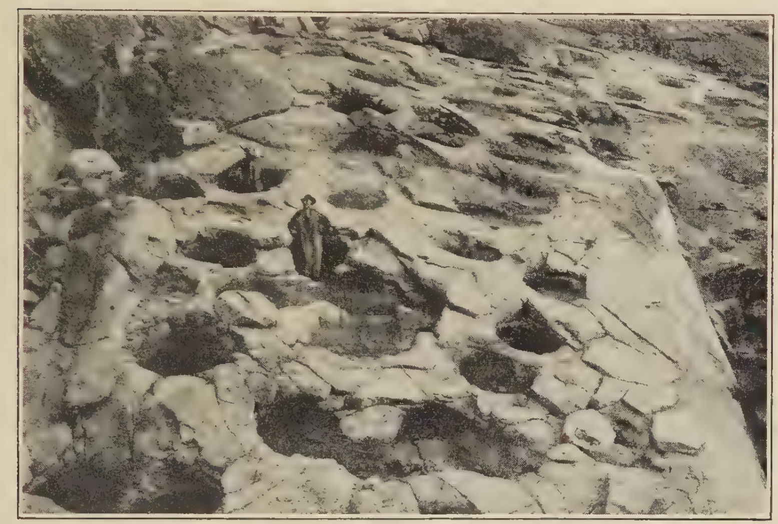

FIG. 31. Potholes in granite, Tuolumne River, California. (Photograph by H. W. Turner. Courtesy of the United States Geological Survey)

The most conspicuous effect of river destruction is the valleys which all rivers develop. A sequence of development for stream valleys from nativity to old age, a program which all streams seem to follow as far as possible, has been conceived and worked out by modern students of earth processes. This concept of the *erosion cycle of rivers* is one of the great constructive ideas of modern geological science.

The cycle of stream erosion. Everybody knows that most rivers grow longer, wider, and deeper with the passage of years, so that with a little imagination we can see that at some vastly earlier date any river was very likely much smaller than at present. The great valley of the Shenandoah was much smaller in the remote past; perhaps at first it was merely a ravine or a gully intermittently carrying water. Though it is quite clear that all gullies do not develop into permanent streams and it does not appear that every permanent stream was once a gully, nevertheless many rivers, perhaps most, had such a modest origin. The struggle which gullies have, and their competition with other gullies in the effort to become permanent stream channels, is a fascinating chapter in physiography. Let it suffice to say here that only occasionally will a gully succeed in capturing from other gullies most of the run-off of a given area so as to be able to deepen itself below the level of the ground water. Here its success as a permanent stream is assured, because the underground water joins with the surface run-off to keep the small valley supplied with water throughout the year. Such young rivers,

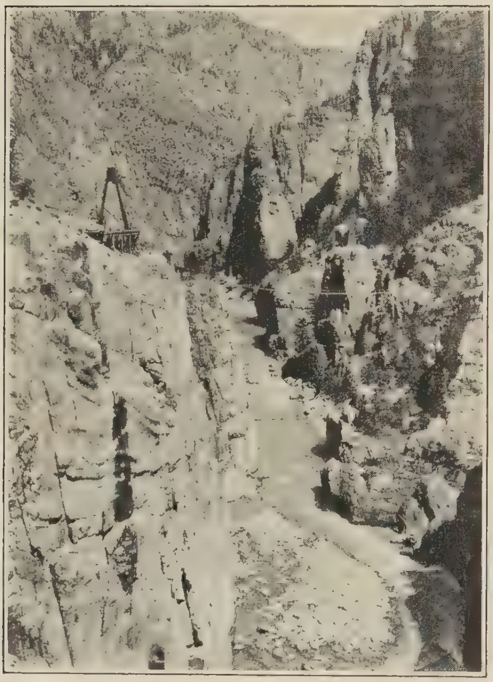

FIG. 32. A youthful river

Canyon of the North Fork of Shoshone River, Wyoming like their older brothers, grow in length *headwardly* through erosion caused by the water which flows in at their upper, steeper ends.

It has long been known that land areas have sunk below the level of the sea to rise again at a later date. On such a new land surface new drainage basins develop to take care of rainfall, and from intermittently flowing streams in gullies there emerge with time a number of young permanent streams. Such young rivers develop the land surface in a way peculiar to themselves (Fig. 33). The valleys are narrow and V-shaped; the ridges between adjacent rivers are wide and comparatively flat. The stream beds are characterized by irregularities in gradient, rapids, and falls, because the streams have not yet had time to smooth out the roughness which their youthful virility has produced on rocks of unequal hardness. There may be lakes occupying undrained basins which have not yet had time to meet the inevitable fate of all such bodies of water—either to be filled by sediment or to be drained by rivers. Tributary streams, which grow in the same manner as their mains, are as yet poorly developed. Such a topography, often characterized by deep canyons and gorges, always with but few permanent streams separated by broad divides, is said to be in the *youthful stage* of the erosion cycle.

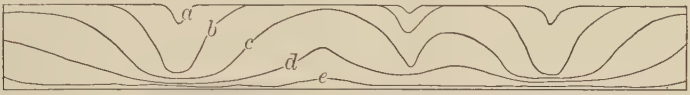

FIG. 33. Diagrammatic cross sections of a region as it develops from the youthful stage, *a*, to the old-age stage, *e*, in the erosion cycle. (Courtesy of W. H. Norton)

With the passage of time young streams smooth out the rapids and waterfalls in their channels; everywhere the divides between main streams are narrowed and converted from steep ridges to gently rounded hills; and tributary streams become more numerous, their valleys more gently sloping. Whereas in youth the streams have steep gradients and transport tremendous quantities of material, in this later, *mature* *stage,* rivers deposit some of their burden before reaching the sea. The topography is rolling and well drained. Lakes have been choked with sediment or sapped by streams. Everywhere are threads of water spreading treelike over the land.

The final stage in the cycle of river erosion must come when streams can no longer denude the land. Since the sea is the goal of most rivers, their work ends, their power is dissipated, and their burdens are dropped when the ocean level is reached. The level of the sea is therefore an impassable barrier below which streams cannot erode. If a surface remains stationary long enough, streams will reduce their gradients so that throughout their courses they flow over slopes just sufficient to permit sluggish movement to the sea. At this point they are close to the theoretical *base level* below which rivers can no longer cut their channels. With the lowering of gradients in the streams the divides become lower, and the land is reduced to a nearly featureless plain, mildly undulating with here and there a pro-

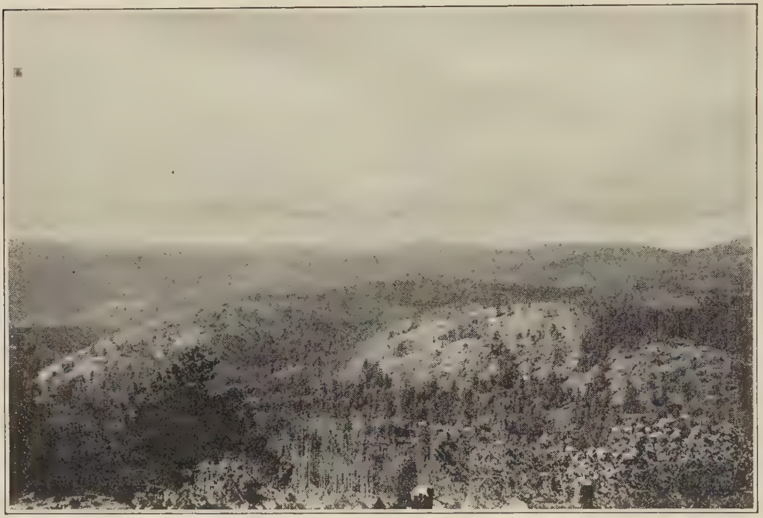

FIG. 34. A peneplain uplifted and dissected by erosion. (Courtesy of the Geological Survey of Canada)

truding knob of land which through superior hardness has resisted all efforts of the rivers to destroy it. Such a rolling topography produced by river wear is called a *peneplain.* Many of the rises in such a "near plain" stand at a common level, and the rivers flow in meandering courses in broad, shallow valleys, depositing much of their load before reaching the sea. In this, the *old-age stage* of the river cycle, the destructive work of erosion has yielded largely to the constructive work of deposition.

Classification of rivers. If a high land is subjected to subaërial erosion for a time sufficiently long, the result will be a low peneplain near sea level, provided that the cycle is not disturbed by earth movement. Normally, however, a land surface is not allowed to progress without interruption from youth to old age. Rivers receive a classification based on the nature of the land over which they flow and with reference to the movements the land has suffered. Certain inequalities will exist on the surface of a newly formed land area raised out of the sea. The depressions naturally invite the excess of rain water, and here the new-born rivers begin life. Such rivers are called *consequent,* because they form in consequence of the original features of the land, and their courses are determined by the relief of the land. Gradually the new rivers grow more independent of the surface over which they flow; more rivers and tributaries form which are not dependent upon the original topography. Such rivers are said to be *subsequent.* Whereas consequent streams flow in accordance with the topography of the land as they find it, subsequent streams excavate courses determined by the structure of the underlying rock. It sometimes happens that during the life history of a river the land below is uplifted. If the stream is strong enough and the uplift not too rapid, the river will cut down as rapidly as the land rises. Such a stream is called *antecedent*; a fine example is the Columbia River, which has persistently cut through mountains rising in its path. Sometimes consequent streams, well adjusted to the original topography, in degrading their channels encounter rock structures of very different nature. They can do nothing but continue in the predetermined courses, so that at a much later date, after erosion has destroyed the original topography, they may be observed to be in quite inharmonious relationship with the country through which they flow. They may have encountered hard rock through which they cut gorges, as no consequent river would do. Rivers, like men, tend to follow the easiest course unless compelled by pressure to act otherwise. When a river flows to the sea in a course clearly out of adjustment with the land surface, it has obviously inherited its position from some preceding topography. Such a river is said to be *superimposed*.

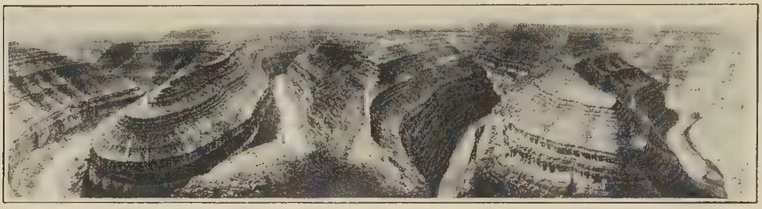

FIG. 35. Incised meanders of the San Juan River, Utah, an old-age stream rejuvenated by uplift. (Courtesy of the United States Geological Survey)

See page 109 for the origin of meanders

Such conditions as varying rock structures and crustal movements change the nature of rivers and affect the cycle of erosion. Old-age streams may be *rejuvenated* by the uplift of the land over which they flow, and begin to cut furiously into their channels so that the land assumes a youthful aspect. While elevation infuses a stream with new life, thus throwing it backward in its cycle, depression has the opposite effect and, by lowering the level of the land that must be reduced, brings on a premature old age. The most conspicuous effects of depression on streams can be seen along seacoasts which have sunk. Streams which enter the sea on such coasts have the lower parts of their valleys drowned by sea water. Such a *drowned valley* is called an *estuary*. Chesapeake Bay is a typical drowned river valley and shows clearly not only how the lower part of the Chesapeake River was flooded by sea water but also how the main stream was bereft of its lower tributaries after the subsidence of the coast. The small streams entering the sea along separate courses on both sides of Chesapeake Bay were once tributaries of the main stream. When the drowning occurred these side streams were cut away and made to shift for themselves. The entire northeastern coast of the United States and the northwestern coast of Europe have suffered recent depressions, so that many estuaries and, as a consequence, many good harbors have been formed. Such disturbances are the rule rather than the exception, so that the cycle of erosion as conceived in theoretical geology seldom takes place without interruption in nature.

UNDERGROUND WATER

We have seen how rivers tend to reduce the irregularities of the land to essential flatness by means of mechanical wear and a small amount of solution. Below, in the recesses of the earth's upper crust, the underground waters are sluggishly working to the sea and slowly doing their bit to destroy the lithosphere. Whereas river destruction is dashing and largely mechanical, ground-water destruction is insidious and almost entirely chemical in its nature. We have seen something of the mechanism of flow in ground water: how it slowly searches its way through pores and crevices, ever seeking lower levels, finally to merge through springs with rivers or to be lost in the bosom of the sea. The chief work of ground water is solution: it is ever picking up soluble substances from the rocks and carrying them elsewhere, often depositing them before the sea is reached. In this way its action is both destructive and constructive; although, since far more material is dissolved than is ever redeposited, the ground water is predominantly an agent of destruction. Large caverns are sometimes leached out of limestone rocks by ground water; in the famous Mammoth Cave in Kentucky the destructive work of this agent is spectacularly shown. Sometimes *sink holes* opening on the surface are formed in conjunction with caverns (Fig. 36). Ground waters are of varying chemical constituency, and the rocks of the earth's crust are of exceedingly heterogeneous chemical make-up, so that an infinite variation from place to place is possible in the destruction accomplished. The chief solvent power of underground water lies in the carbon dioxide and organic acids received from the air and soil through which rain water must pass to penetrate the crust. The effect of ground water enriched in this way is felt largely by the sodium, calcium, iron, and magnesium carbonates so plentifully present in the outer parts of the lithosphere.

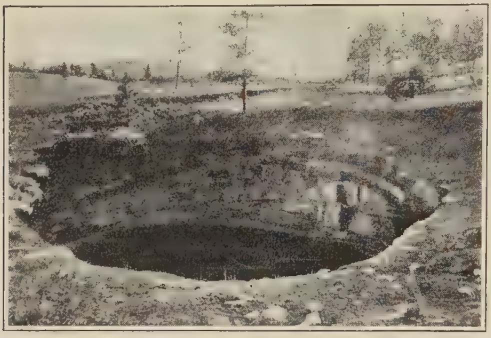

FIG. 36. A sink hole in Wyoming. (Photograph by W. W. Atwood. Courtesy of the United States Geological Survey)

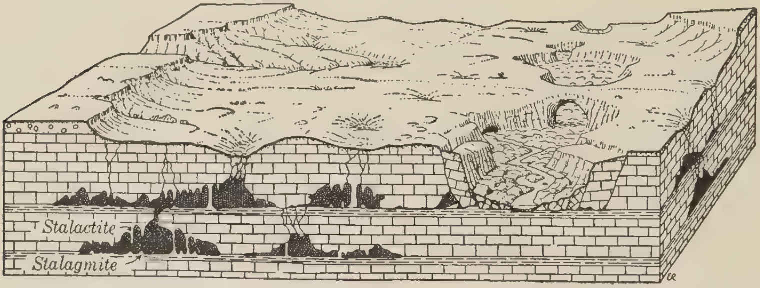

FIG. 37. Diagram showing the formation of caves and sink holes in limestone
At the right is a natural bridge, vestige of the roof of a former cavern

The mechanical work of ground water in causing *landslides* is important geologically in mountainous regions and is sometimes of great concern to man. Certain soft rocks when saturated with water act as a fluid and, particularly in mountainous regions, may cause overlying harder rock to start from its insecure position and slide to the valley below. Heavy rain, frost, and earthquakes materially aid the consummation of landslides, although a soft rock surface well lubricated by ground water is usually a necessary prerequisite.

SNOW AND ICE

Popular literature has frequently alluded to the "Ice Age," so that most people are aware that at an earlier time in the history of the earth ice and snow were more abundant than now. The earth, in fact, has seen many ice ages which have left abundant records in the rocks. The last great ice age, known as the Pleistocene, is not so far in the past but that abundant evidence of its proximity is seen on the present surface of the earth. Not only the indications of glacial erosion and deposition, but likewise the ice which still clings to the polar regions and the high mountains of the globe, give proof of our nearness to a great ice age. Greenland, which once felt the warmth that enabled the palm and the magnolia to flourish, is now a desolate waste almost entirely covered with perennial snow and ice. To the vast areas perpetually covered with snow and ice there must be added most of the remainder of the land surface, which is frozen during a part of each year. We are, perhaps, just emerging from the Pleistocene ice age, and today ice and snow are still important agencies of geological work.

Nonglacial Ice

While the greatest amount of work done by ice is accomplished by glaciers, a factor not to be neglected in land alteration is the work done by the ice in soil, rivers, lakes, and the sea. The work of frost in blasting rocks has already been recounted. Since water expands upon freezing, soil is loosened, and objects driven into it, such as fence posts, are gradually lifted vertically and are often so weakened as to fall down. The power of frost to lift objects aids materially the movement of loose material down slopes. In rivers, ice aids considerably in the transportation of débris by freezing to the sides and bottoms of the stream channels and carrying along loose pieces of rock after the ice breaks up in the spring.

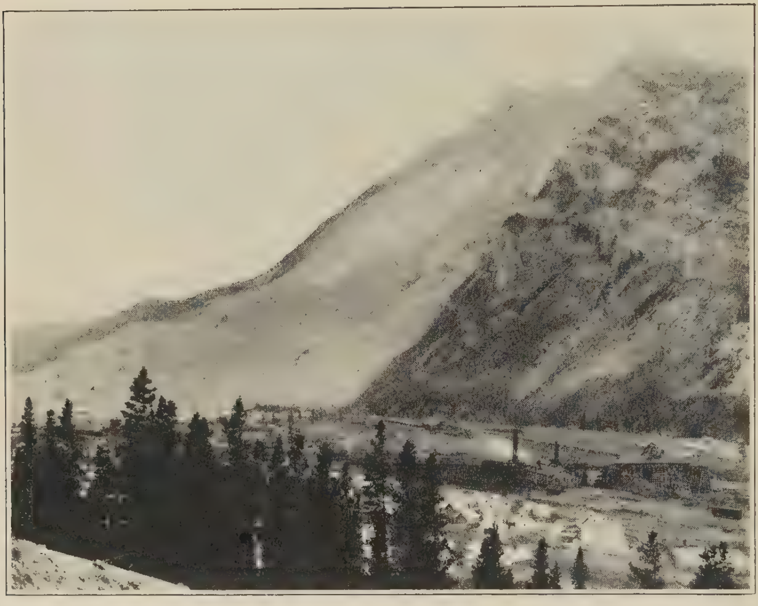

FIG. 38. The great landslide on Turtle Mountain, Alberta. (Photograph by R. A. Daly. Courtesy of the Geological Survey of Canada)

In 1902 a large segment of this mountain slipped into the valley, burying homes and killing many of the inhabitants of the coal-mining town of Frank

When ice forms in lakes a great thrust is exerted along the shores, often pushing rock material into ridges (*ice ramparts*) (Fig. 39). Although most of the ice in the oceans comes from glaciers entering the sea in high latitudes, *icebergs* and *ice floes* can hardly be classified under glaciers. Such moving ice transports large quantities of rock from high to low latitudes, and has probably in the past aided in the distribution of living creatures. It is not uncommon to see animals of various types marooned on large icebergs, and such involuntary voyagers may by a lucky chance reach new lands, although undoubtedly most of them are doomed to be drowned when their ephemeral homes melt and disappear.

GLACIAL ICE

Glaciers take origin on mountain tops and polar lands. Even in tropical regions, amid the lofty crags of towering mountains, perpetual snow fields exist. All such fields are terminated below by a line beyond which the temperature is too high or the snow supply too scant to permit further downward extension of permanent snow. This *snow line* is near sea level in high latitudes, but toward the equator it gradually rises until it lies near the summits of the highest mountain peaks. Above the snow line, where snow supply exceeds snow waste, glaciers are born.

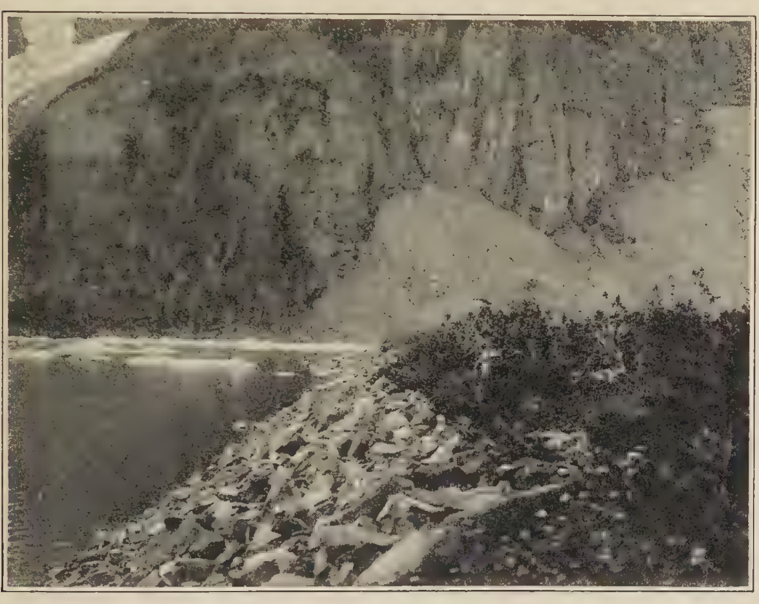

FIG. 39. Ice rampart on the shore of Iceberg Lake, Glacier National Park. (Courtesy of Dr. M. J. Elrod)

Origin of glaciers. The loosely compacted water crystals called snow undergo a remarkable transformation in the snow field. The once feathery flakes of new-fallen snow are gradually compacted under the pressure of each annual accumulation and changed into hard pellets resembling coarse-grained sand. Such fields of granular snow, usually lodged in hollows on the flanks of high mountains above the snow line, are called *névé fields,* and the accumulation of much of the snow of many winters makes these fields the birthplaces of glaciers. Toward the bottom of the névé slopes the snow is so thoroughly compacted as to be called ice. This ice is usually stratified because it is made up of successive falls of snow of somewhat different textures separated by intervals without snowfall, during which time the snow already accumulated may undergo change and be covered by wind-blown earthy material. The ice born of névé resembles its parent in being made up of crystalline grains, but differs from it in that the grains are larger and more intimately grown together.

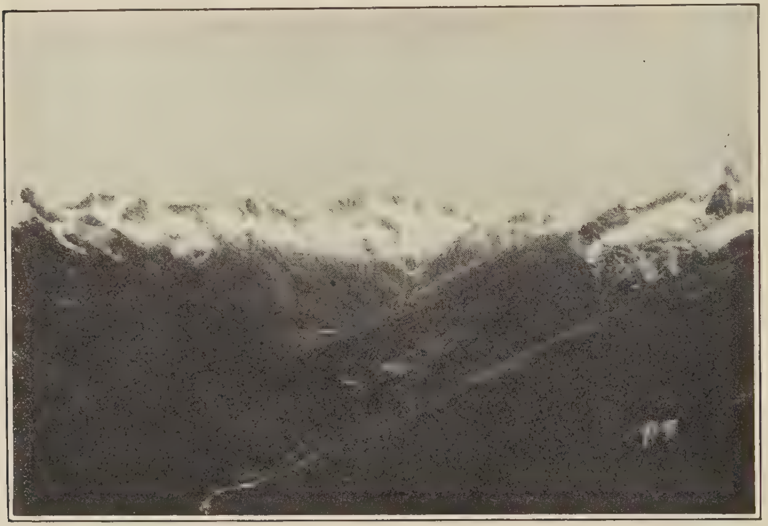

FIG. 40. Snow line in the Swiss Alps. (Courtesy of Dr. R. T. Chamberlin)

Glacial movement. When snow and ice accumulate to sufficient depth, movement takes place down the slope of the névé field. Any valley makes a convenient outlet for the overloaded basin filled with ice and snow. Through this valley the glacier flows, much like a true river. While there exists a slow motion in the névé field above the point at which the glacier proper begins, there is usually a place where the movement is sufficiently accelerated to produce a yawning chasm between the snow-field névé above and the true glacier below. This *master crevasse,* or *bergschrund,* lies at or near the snow line and marks the beginning of all true glaciers (Fig. 41).

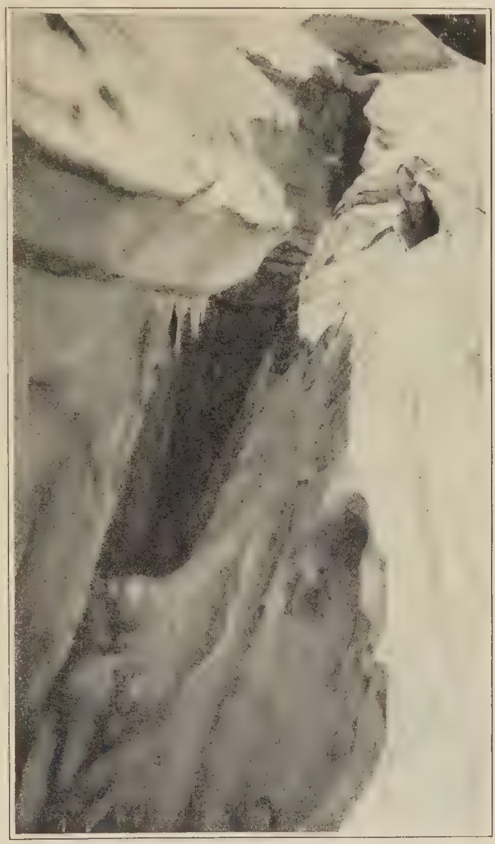

FIG. 41. The bergschrund of a glacier. (Courtesy of the United States Geological Survey)

Glacial movement, still much of a mystery, is remarkable in that through it the ice of glaciers shows itself to be a substance of dual personality — an exceedingly brittle solid yielding with a snap to sharp, quick pressure, but acting like a plastic body when subjected to long-sustained pressure. When movement takes place with a jerk, glaciers are rent by deep cracks and fissures; but normal glacial movement is slow and sinuous, like that of a thick, viscous fluid, producing molecular changes within the constituting granules of ice.

The analogy between glacial movement and movement in a viscous fluid is only superficial. From its origin in the snow of the snow field through the gradual rounding and compacting of the water crystals in the névé field and in the glacier itself, a glacier is never anything but a crystalline body with the properties of crystalline substances and subject to the laws that govern such substances. The cause which initiates and sustains glacial movement is the melting and refreezing of the thin surface film of the ice granules in the glacier while the ice as a whole remains rigidly crystalline. Glacial movement is induced, therefore, by the momentary lubrication of melting on the surface of the ice pellets of which all glaciers are constituted; so while the effect is the apparently easy flow of a thick fluid, in reality the glacier remains preponderantly solid throughout, in accordance with its crystalline nature.

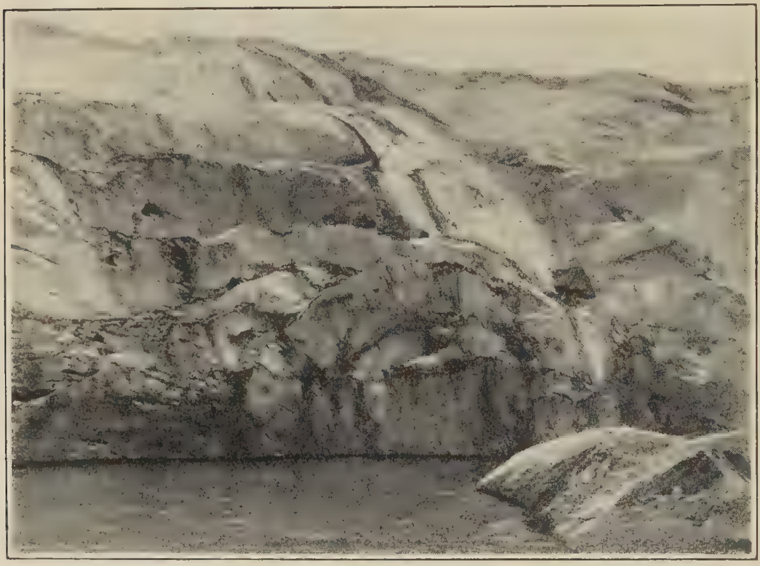

FIG. 42. The sheared ice front of Mendenhall glacier, Alaska

Toward the lower portion of a glacier the combined effect of vertical pressure and thrust from above in many cases results in shearing (Fig. 42). The layers of ice are apt to be successively thrust forward one over another. The planes of shearing, while probably determined by an alignment of granules, are due to sudden relief from stress and not to the slow molecular movement of the whole mass. The strain of passing over irregularities in its bed sometimes produces on the surface of the ice tension stresses to which the glacier yields by cracking to form the *crevasses* which are ever-present dangers to the Alpine climber (Fig. 43).

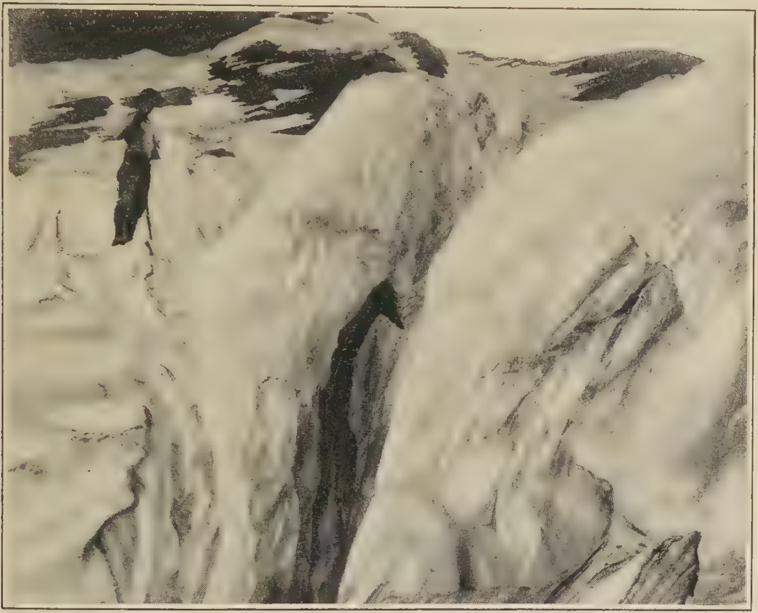

FIG. 43. A longitudinal crevasse in Blackfoot glacier, Glacier National Park, Montana. (Courtesy of Dr. M. J. Elrod)

Snow bridges, such as the one shown, make it possible for mountaineers to cross glaciers

The movement of glaciers is very slow; those in the Alps move from one to three feet a day, and some of the faster-advancing Greenland glaciers move as much as sixty feet a day. Compared with the flow of even sluggish rivers, such a rate is exceedingly slow. Like rivers, glaciers move faster in some parts of their channels than in others, depending upon the gradient of their slopes.

Classification of glaciers. Glaciers are classified according to their size and the nature of the topography where they exist. The best known are those which form on high mountains all over the world. These are known as *mountain* glaciers; they usually spring from broad amphitheaters, or *cirques*, high in the mountains. Rocky walls usually rise precipitously around such cirques, forming strikingly beautiful elements in the scenery of lofty mountain ranges. Such sheer-walled amphitheaters are produced by the gnawing action of glaciers at their bases, where they pull away from the névé field above. Cirques are the feeding grounds of the typical mountain glacier and are highly characteristic of this

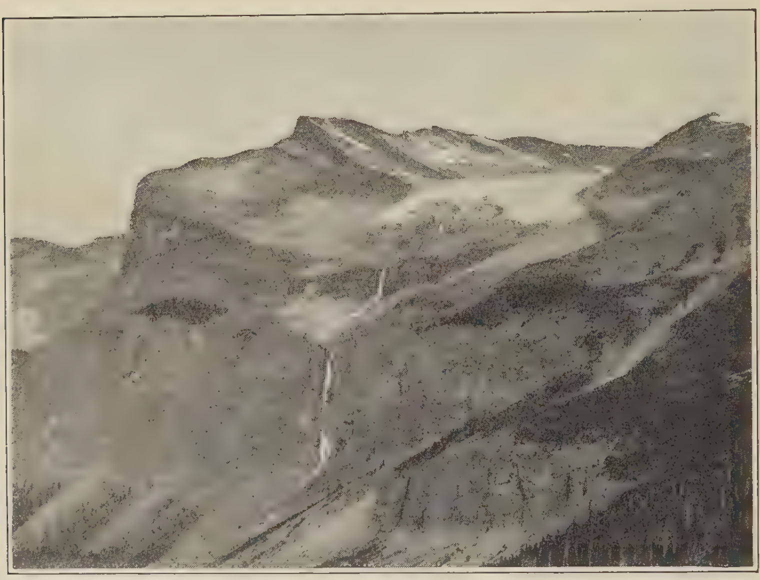

FIG. 44. A small mountain glacier occupying a cirque in the President Range, British Columbia

type. Many of the small mountain glaciers of the Rockies and elsewhere are not typical in that they have not developed cirques, but consist of patches of snow and ice clinging to cliffs, without a true moving glacial tongue below. Others are intermediate between névé ice fields without well-developed glacial outlet and those possessing such an outlet.

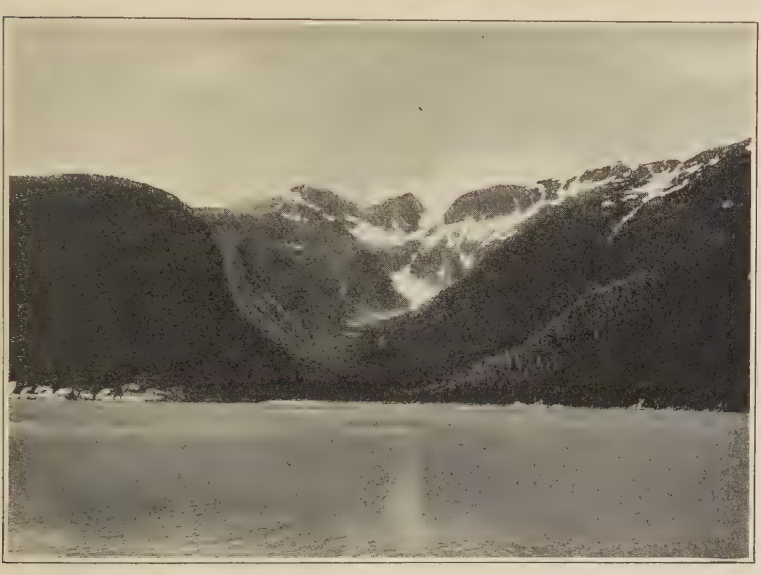

FIG. 45. A cirque in Alaska

Sometimes glaciers flow well below the snow fields which give rise to them and occupy upland valleys in high mountainous regions. These glaciers, known as *valley glaciers,* give rise to the metaphor "a river of ice." Where valley glaciers descend from the mountains to more level country below, they are called *piedmont* glaciers. This type is confined largely to high latitudes where low elevations are cold enough to sustain glaciers.

Most important in geological history have been the *ice caps* — vast sheets of ice sometimes covering large portions of a continent. Greenland today suffers the burden of such an ice cap, and so does the continent of Antarctica. The great Pleistocene ice caps, so important in their effect upon the scenery and life of the lands of the Northern Hemisphere, will be considered in more detail later.

Destruction wrought by glacial ice. Like rivers, glaciers wear down the rocks over which they flow and carry material from one place to another, grinding it as they go. Under the slowly moving névé fields erosion is initiated by a process known as *plucking*. Ice freezing in the cracks or joints of the underlying bedrock pulls away chunks of rock bounded by these preëxistent planes of division and slowly carries them along. The plucking power of the ice becomes tremendous at the place where the glaciers proper break away from the névé slopes. Here, where the master crevasse is developed, the work of loading the glacier with rock débris begins in earnest. During summer days, when thawing on the surface of the ice is active, water finds its way down the sides of this great fissure to be frozen at night to the rocky material at the bottom. Since motion is accelerated at this point, blocks of

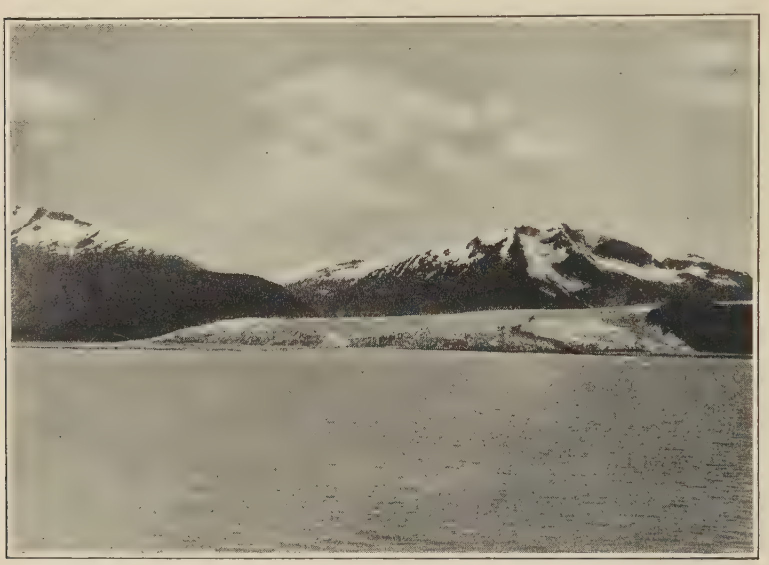

FIG. 46. A valley glacier entering tide water in Taku Inlet, Alaska

rock frozen to the ice are loosened and are slowly inclosed by the glacier and carried away. In this way the glacier digs a hollow in the rocky side of the mountain and slowly eats down, thus forming with time the sheer-walled cirques so characteristic of glaciated mountains. The plucking action of glaciers at the bergschrund, working backward as well as downward, may ultimately gnaw off the head of a mountain. One of the striking peculiarities of some Alpine ranges is that all the peaks constituting them rise to a common level. Since the level of the bergschrund of all the higher glaciers in a particular mountain range is thought by some to be determined by the snow line, an accordance of summit levels may be explained by the decapitation of each peak by glaciers eating into the mountains at the critical and fatal belt of the master crevasse. Although many other factors must be considered in explaining accordant summit levels, let it suffice here to emphasize that in all glaciated moun-

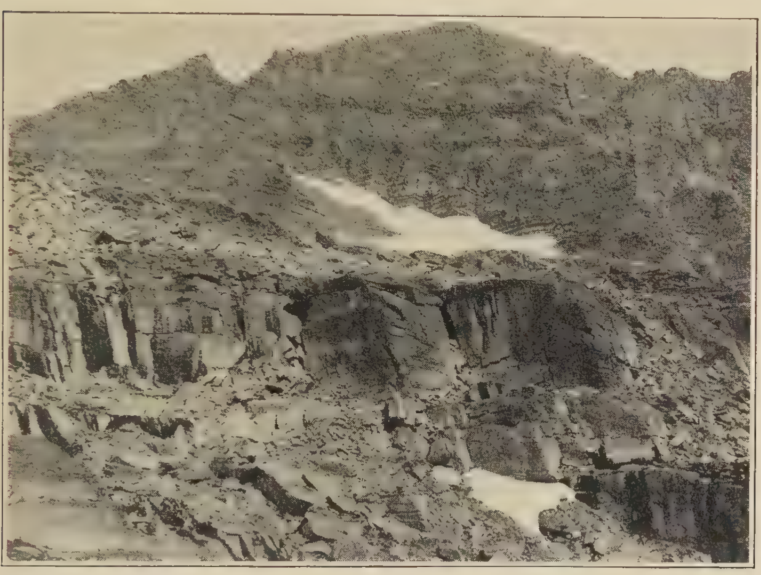

FIG. 47. Cirque wall in Glacier National Park showing the effects of plucking

tains the belt of the bergschrund is an open sore which is never healed as long as climatic conditions are favorable to the existence of glaciers.

Below the master crevasse at the head of the glacier, where true glacial movement begins, a new and totally different type of erosive destruction sets in. While plucking action continues along the joint planes in the bedrock wherever the ice is in motion, this type of denudation is of but secondary importance below the bergschrund. The rocks obtained from the bed by plucking become firmly frozen in the bottom of the moving ice, forming a merciless rasp, which, loaded by the enormous pressure of the ice above, gouges grooves in the bedrock below. In this way glaciers wear away the valleys through which they move. The sides of valleys are likewise ruthlessly worn away by the onward march: first, the protruding edges of rock; later, by means of new tools firmly embedded in its sides, the monster of destruction

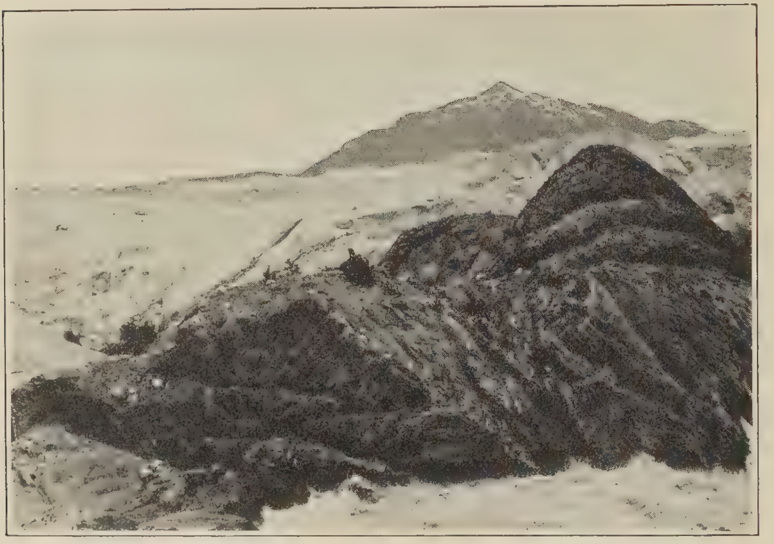

FIG. 48. Glacial destruction

An Alaskan glacier reducing its valley by both ice and water action scratches deeper into the confining walls. Gathering material as it advances, by rasping and plucking, and in other ways, the glacier marches down its valley, greedily devouring any obstruction to its easy flow and gradually becoming heavily loaded with a burden of rock débris.

The rocky materials picked up by glaciers are of diverse nature. Stones in the ice rubbing against each other or gouging into the bedrock produce a finely divided rock powder called *rock flour*. Fine clay of this type and stones of all sizes up to huge bowlders characterize the surface and bottom of all glaciers. Even the interior of glaciers has its share of rocky material ingested through the crevasses, which open under the strain of the moving ice.

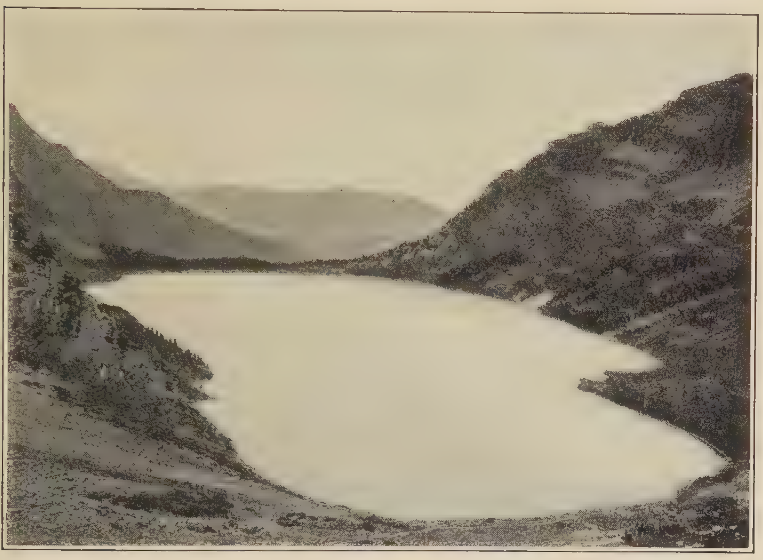

FIG. 49. A lake occupying the cirque of a glacier now extinct

Lakes of this type are plentiful in many regions of lofty mountains and are called *rock-basin lakes*, or tarns. This is Lake Ellen Wilson, Glacier National Park

Effect of glaciers on the landscape. Glaciers, like all earthly things, are evanescent phenomena. The dignified drapery of snow and ice on the noblest peak today will, after the passage of an inestimable length of time, disappear just as it has disappeared on other peaks. Many mountains now denuded of their glacial adornment give clear and striking testimony of the great ice sheets which once graced their slopes. Glaciers leave behind them unmistakable evidence of their former existence, whether on mountain top or on piedmont slope or on continental plain, long after they have melted away.

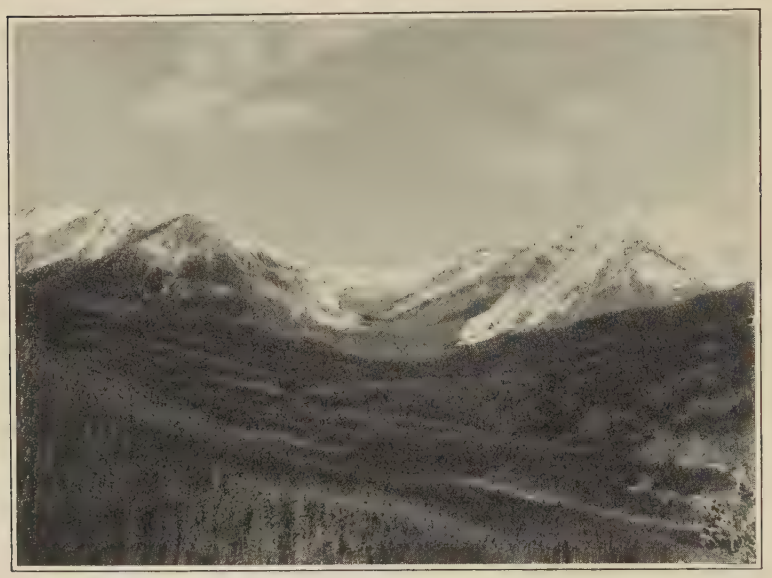

FIG. 50. A typical U-shaped glacial valley in Montana. (Photograph by K. D. Swan. Courtesy of the United States Forest Service)

The most important effect of glacial ice on the topography of a region is seen in the valleys. The normal valley produced by river erosion is V-shaped, because all destructive processes focus in the channel of the stream; the glaciated valley is characteristically U-shaped, because vigorous erosion takes place not only along the bottom of the channel but along the sides as far as the ice extends (Fig. 50). The tributaries of rivers enter their mains at grade, that is, on a common level. Tributaries of glaciers, on the other hand, cannot cut down their channels as rapidly as the main glaciers can, and so their lower ends are apt to be hung high up on the sides of the main valley. Valleys made in this way are called *hanging valleys*; they are common in most high mountains (Fig. 51). After the ice has abandoned its work, water may take its place, with the result that high waterfalls are produced when the new river drops from the level of the mouth of the old tributary valley to the main valley, often far below. Such waterfalls contribute some of the finest scenic effects to be observed in the mountains of the western part of North America.

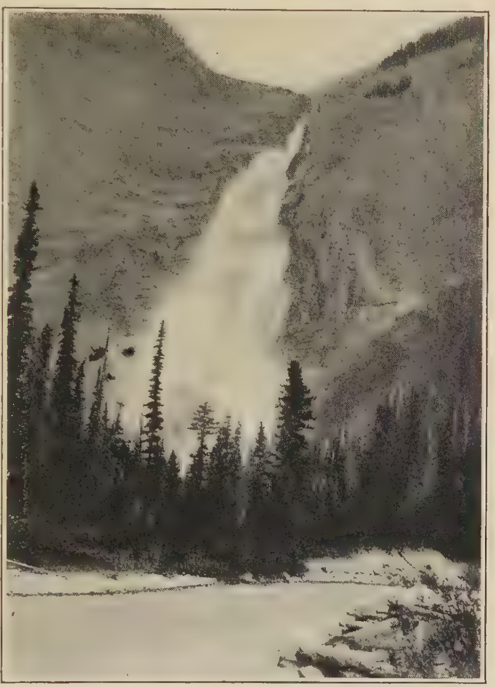

FIG. 51. The hanging valley from which descends Takakkaw Falls, 1200 feet high

The Daly glacier lies back of the falls and supplies the water. The main valley, from which the picture was taken, is Yoho Valley, British Columbia. The Yoho glacier to the north is but a shrunken remnant of the great ice river which once occupied the valley

Along the coasts of many lands (notably Alaska, Labrador, Norway, and Chile), where glaciers have descended into the heads of narrow bays, elongating the bays by erosion inland, typical U-shaped glacial valleys, communicating with the open sea, can be seen in places abandoned by the ice. Such valleys are called *fiords*, and in them glacial erosion has actually proceeded below sea level. When the glacier melted away, the sea entered the overdeepened valley (Fig. 52).

The detailed aspect of glaciated terranes where the ice has stripped its bed of all removable material is generally smooth, roundly grooved, or even polished. Small pebbles and sand pulled over a rock surface by the moving ice produce innumerable scratches, or *striæ*, and larger bowlders make furrows, or grooves (Figs. 53, 54). Often a projecting hummock of rock lying in the path of a glacier is worn smooth and round on the upstream, or *struck*, side, but is plucked on the downstream, or *lee*, side so that its wall is steep and rough. When viewed from a distance such glaciated half domes of rock resemble small flocks of sheep; they go by the Swiss name *roches moutonnées* ("sheep rocks"). "Sheep rocks" are common in regions once occupied by great continental ice caps. New England is such a region. Its topography may be said to be Janus-faced, because to one looking

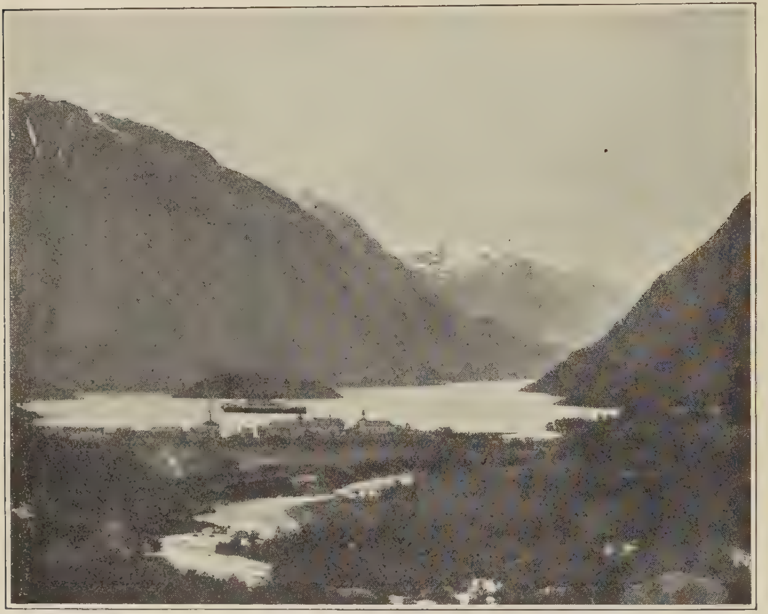

FIG. 52. A fiord, Odde, Norway, showing a glacial stream in the foreground. (Photograph by Ewing Galloway, New York)

southward along the line of the ancient ice advance the landscape appears smooth and free from all jutting angles of rock, but when one turns northward toward the plucked side of glaciated rocks the view is rough and rocky.

Glaciers, on disappearing, build up the lands they have devastated by depositing their heterogeneous rocky burdens in a way wholly characteristic. This reconstructive phase of the life history of moving ice will be considered in the next chapter, which considers the surface processes of construction.

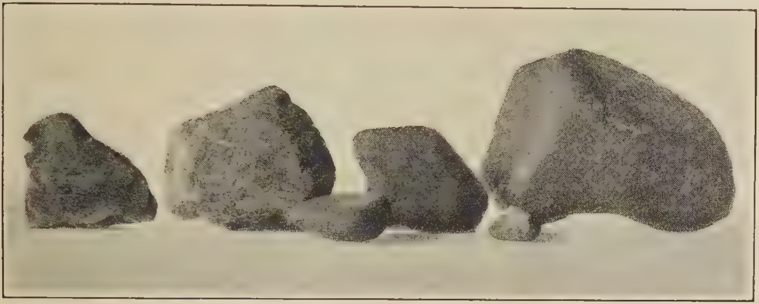

FIG. 53. Pebbles smoothed, faceted, and striated by moving ice. (Photograph by Alden. Courtesy of the United States Geological Survey)

Glacial climates. One of the great problems in geology is the reason for the repeated occurrence of glacial climates on the earth. The earth is just now passing out of such an ice epoch, when all the continents of the Northern Hemisphere were in large part covered by thick sheets of ice. In North America, for instance, the ice reached as far south as latitude 36° 30″ in the vicinity of Cairo, Illinois. We might, indeed, consider the earth still partly within the control of this glacial climate, since the polar regions, nearly all of Greenland, and all high mountains are covered with ice. One of the peculiarities of glacial climates is that within a relatively short time geologically the ice may withdraw and be replaced by warm-climate plants and animals, which in turn are later replaced by the desolation of a continental ice cap. The more we study glacial climates of the past through the records of ice work left behind in the rocks, the more evident does it become that ice ages alternate with interglacial epochs whose climate is mild. Then, too, it would seem that the earth was never at a given time entirely under the control of a glacial climate. The ice is always more or less localized. Oddly enough, the ice of all glacial times was not restricted to the polar regions and high altitudes as in the case of the last glacial period. In at least one great glacial period of the past, large ice fields of continental proportions formed at low altitudes in the equatorial belts of India, Africa, and South America! The phenomena of (1) the repeated alternation of glacial and warm climates, (2) the localization of continental ice sheets, and (3) their presence in low altitudes and latitudes are among the most profound problems of all science. Although many explanations have been offered, no universally acceptable hypothesis

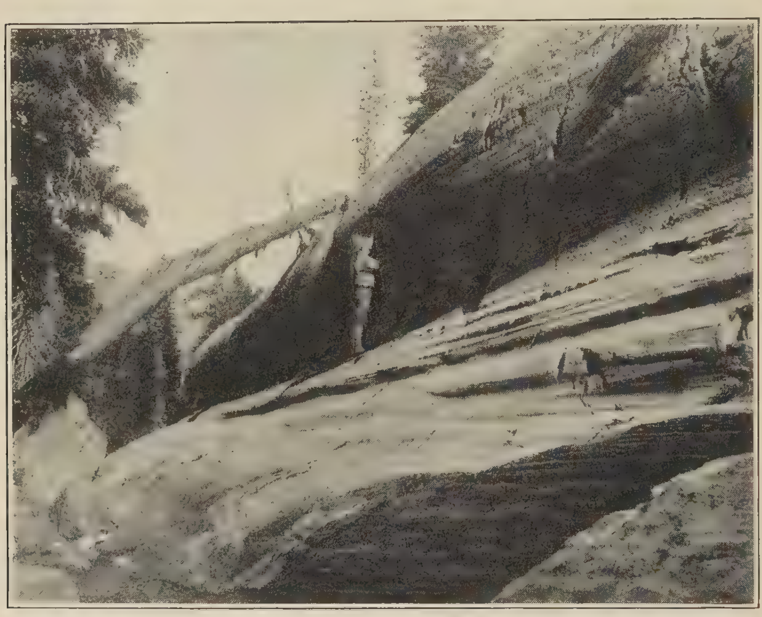

FIG. 54. A giant glacial groove, Mission Range, Montana. (Photograph by Asahel Curtis. Courtesy of the United States Forest Service)

for the causes of glaciation has yet been produced. The heavens have been searched for extramundane causation; the seas and the interior of the earth have been invoked; but to little avail. The secret of the cause of glacial climates seems to lie in the atmosphere, and is now quite generally thought to be intimately tied up with the carbon-dioxide and water-vapor content. It is known that the heat of the atmosphere (and therefore the surface of the lithosphere and the hydrosphere) is controlled by the amount of these two gases present in the air. At times of widespread coal formation and limestone deposition the atmosphere becomes weaker in carbon-dioxide vapor, with cold climate the normal result. The presence of large quantities of volcanic dust in the air would likewise tend to bring on a glacial climate. Atmospheric dust not only acts as an umbrella which deflects some of the radiant energy of the sun from the earth's surface, but also presents nuclei of condensation for the water vapor in the air.

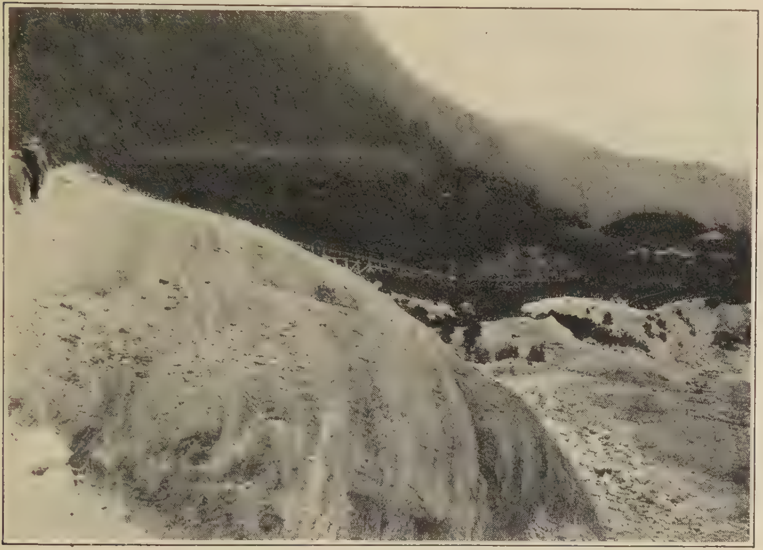

FIG. 55. Glaciated rock dome in Alaska produced by a valley glacier

A long chain of attendant and resultant phenomena are thought to occur under these conditions, all tending to the production of glacial and interglacial climates. The problem is far too involved for elementary treatment, and we must leave it here, remembering that whatever causes the impoverishment of carbon dioxide and water in the air likewise causes glaciation. It can be seen without further discussion that although this impoverishment can be explained as the result of extensive coal formation and explosive volcanic activity — processes which draw carbon dioxide and water from the air — it is not so easy to explain the relatively rapid reversal of the process which must have occurred to produce the warm interglacial climates. In like manner the reason why one area should be glaciated and another not, *at the same time* in geological history, and why in one glacial period low altitudes on the equator should suffer and in another high altitudes and polar regions, is still unknown. It is to this point that modern geological science has grown. The causes of glaciation are somewhere hidden in the activities of the atmosphere, and from the study of the atmosphere we can hope for a solution of these problems.

THE OCEAN

The ocean, in covering nearly three fourths of the surface of the earth, is the most colossal instrument of geological work on the surface portion of the globe. Its power to destroy land as well as to build it up is exceedingly slight in comparison with its tremendous bulk. All processes of terrestrial erosion tend to reduce the land to the level of the ocean; the sea is the great repository of earthly waste. By the deposition of such material at the mouths of rivers and its distribution by currents, a great amount of reconstructive work is accomplished in the ocean.

The destructive work done by the ocean along seacoasts is in most cases more spectacular than important. The bark of the sea is truly worse than its bite, although the writings of early geologists in the British Isles attribute great and undue significance to the effects the sea produces on the land.

Like most other physical instruments of land alteration, the ocean receives its power to destroy through its movement. We have seen that three separate and distinct types of motion agitate the sea: waves, currents, and tides. Of these, waves alone are of any significance as instruments of rock wear.

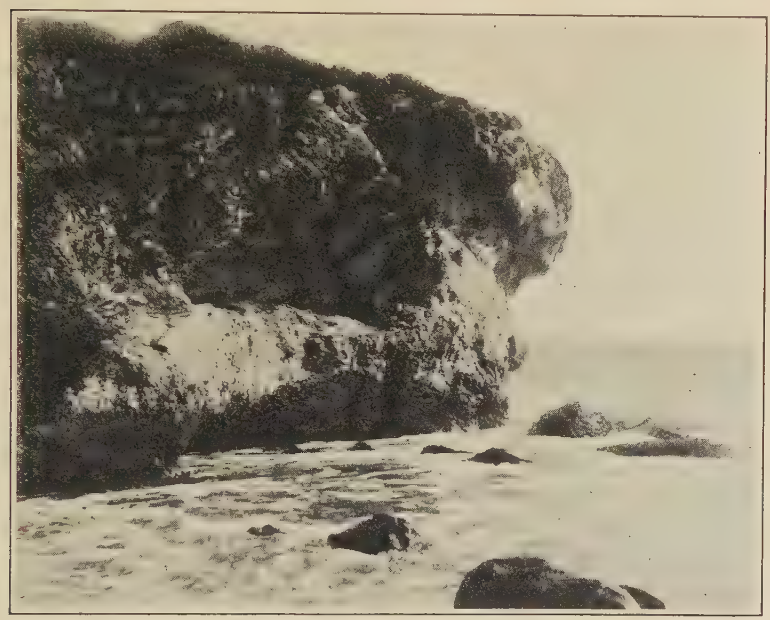

FIG. 56. A sea cliff with caves at different levels. (Courtesy of Dr. R. T. Chamberlin)

The caves were produced by wave erosion; so the presence of the upper one proves a recent uplift of the shore line in this place

Waves, like rivers, work largely by mechanical means, although sea water has a slight ability to dissolve many kinds of rocks, and unites this chemical power to its more important physical power in an attack upon the rocks along the shores. Like rivers, waves not only wear down the rocks they attack but also carry away the products of wear and deposit them elsewhere.

The sheer impact of pure sea water against a rocky coast often does considerable damage by pounding into cracks and fissures, ultimately dislodging and removing large chunks of rock. Such a water wedge is materially strengthened by the air which is impounded into crevices with the water. When the wave recedes this entrapped air is sucked out, leaving behind a partial vacuum, which aids in removing rock material. Prolonged attack of this type results in the *sea caves* and "spouting horns" familiar to the inhabitants of rocky seashores.

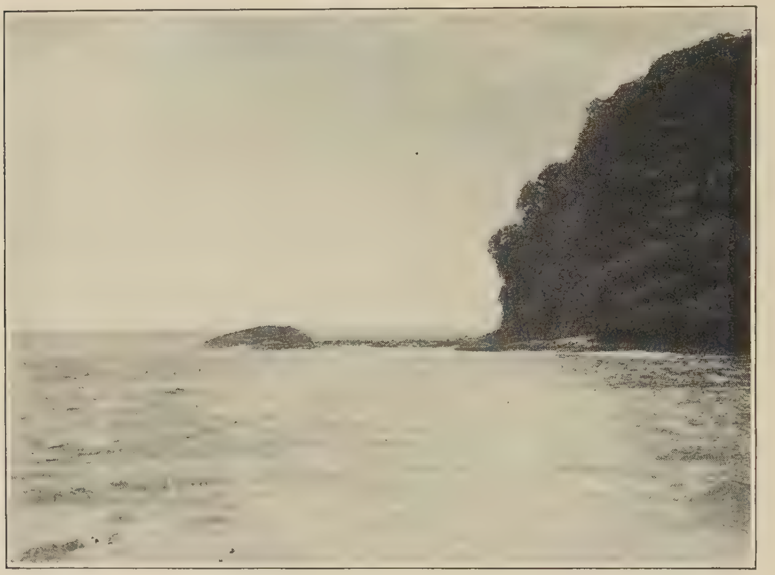

FIG. 57. A sea cliff with well-developed sea bench. (Courtesy of Dr. R. T. Chamberlin)

Recent uplift has raised the sea bench above the surface of the ocean

The most effective work done by ocean waves, as by river currents, is accomplished with the aid of tools; silt, sand, gravel, and sometimes even large bowlders carried by the angry waves are formidable instruments of destruction. With time the tools themselves wear out and are gradually rounded and broken into smaller and smaller bits, which are retired from the field of action by the undertow, perhaps later to be swept away by shore currents and finally thrown up on a beach by waves. Fresh supply of rock débris is furnished by the materials worn by the waves from the shore, which in turn is rounded and carried away by undertow and currents. Waves working in this way on steep shores may cut back into the land to produce *sea cliffs* and *sea benches* (Fig. 57).

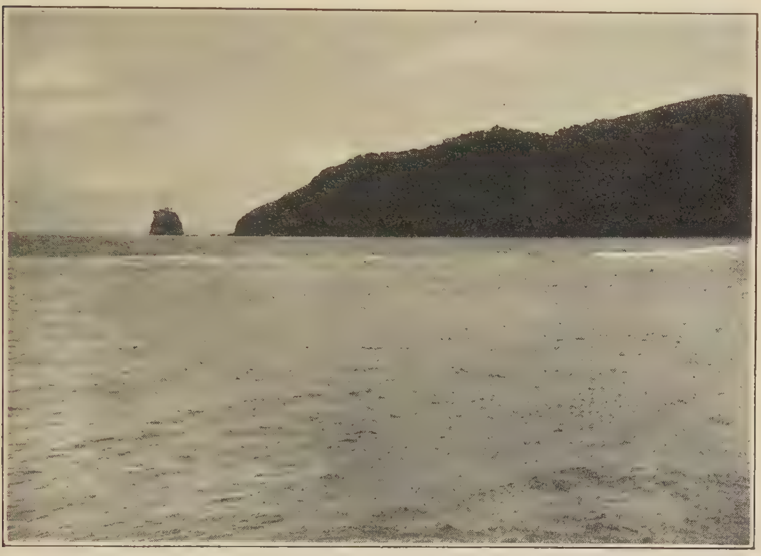

FIG. 58. A sea stack in the Hawaiian Islands. (Courtesy of Dr. R. T. Chamberlin)

Sometimes waves working around a rocky headland from both sides succeed in separating a portion of such a promontory as an island. In some cases just a pinnacle of rock (*sea stack*) is left behind as a reminder of the land that once existed (Fig. 58).

ORGANISMS

Last but not least among the influences which conspire to destroy the lithosphere are living creatures, both plants and animals. Like the other agencies discussed in this chapter, life not only destroys the lithosphere but likewise builds it up. In the present discussion only the former phase of activity is considered.

In producing geological change plants are of far greater importance than animals because of their habit of taking carbon-dioxide gas from the atmosphere and storing it in their tissues while performing their life functions. On the decay of the plant the carbon dioxide is given over to the soil, together with other acids generated in the plant body during life. During life as well as during the decay following death, plants give off acids which are powerful solvents of rock substances. Much of the chemical work done by underground water is made possible through the potent solvents which are turned into the soil by plant life and which rain water absorbs as it seeps downward.

The mechanical work of plants, particularly the roots of trees and shrubs penetrating the cracks in rocks, has been observed by all. The sum total of destruction wrought in a single year by this means is large.

The destruction wrought by animal life is largely mechanical and is greatest among animals that live and move about in the ground. Gophers and other burrowing rodents, ants, and especially worms are continually upturning soil and facilitating the work of weathering and erosion. The classic research of Charles Darwin showed the great value of earthworms to the agriculturist as tillers of the soil. This modest creature, through its habit of ingesting soil for what food it may obtain and then bringing to the surface the earthy residue, succeeds in the aggregate in moving and disturbing large quantities of earth. In the area in England studied, Darwin estimated that earthworms bring ten tons of soil to the surface of every acre of land every year.

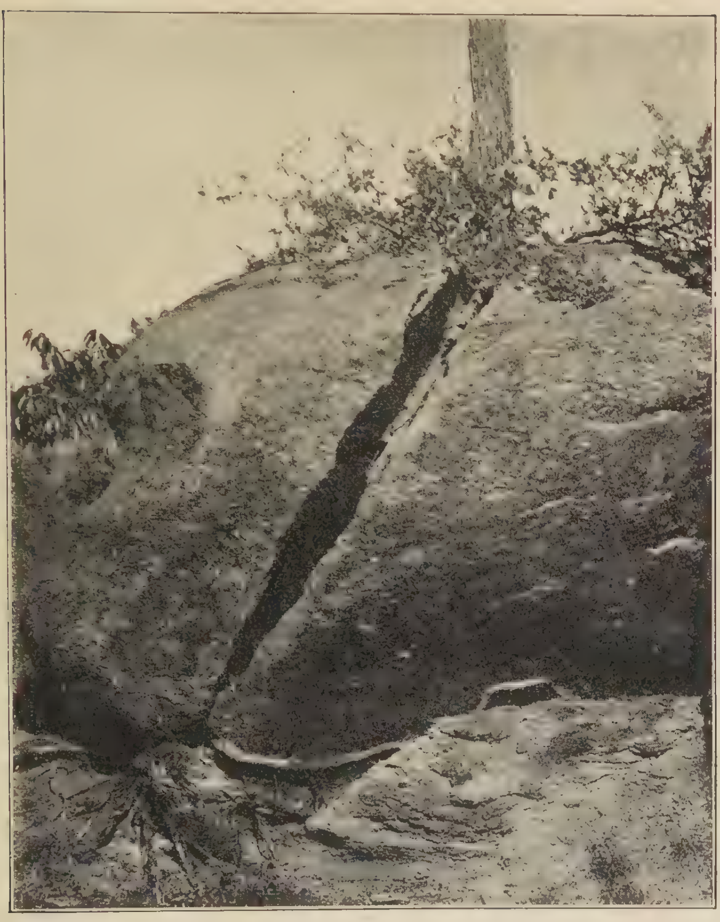

FIG. 59. A tree disrupting a rock. (Reprinted by permission from "General Science," by W. H. Snyder. Published by Allyn & Bacon)

The destruction dealt by man is probably greater than that of any other living creature. By destroying forests, which are nature's greatest protection against erosion, by disturbing drainage, by extending the geographic distribution of some plants and animals and exterminating others, man during his relatively brief history has taken his place among the more important agencies of destruction.

To a lesser extent than plants, animals secrete, in their body liquors and by decay after death, certain chemical substances which work destructively upon rock. In tropical countries much important geological work is accomplished by ants. In places they honeycomb the soil with their tunnels, thus providing an entrance for air and rain. By carrying into their burrows leaves, which liberate carbon dioxide upon decay, and by generating carbon dioxide while performing their own vital functions, ants contribute to the chemical destruction of the lithosphere. In much the same way sea-dwelling animals of low organization secrete acids that attack and destroy shells and rocks composed of limestone.

CHAPTER III

SURFACE PROCESSES OF CONSTRUCTION

If the agencies of destruction described in the last chapter were allowed to work unchecked, the lands of the earth would long ages ago have been reduced to sea level, inundated, and rendered unfit for habitation. We shall now consider the processes which check or tend to retard the ever-degrading action of destructive agencies and which make the history of continents the story of a ceaseless struggle between forces of destruction and construction.

Quite apart from the periodic reëlevation of lands and the volcanic unrest which often results in the reinvigoration of worn-out continents, the very agencies whose chief task it is to destroy often develop as a by-product of their energy certain tendencies to rebuild the land they set out to tear down. It is these surface processes of reconstruction that must now be considered.

A large part of the rock débris produced by the wear of weather, the scouring of rivers and moving ice, and all the other agents of degradation never reaches the sea. The powers of such agencies are localized, and are greater at some times than at others, so that more material is loosened and started seaward than ever reaches its destination. Some rock waste is left on the land. Although the agencies of destruction may degrade and destroy the preëxisting topography of continents, they cannot destroy the materials out of which such lands are composed. These are sooner or later deposited somewhere, and there a new cycle of construction begins. While erosion ever strives to strip the land bare of loose material and wear down consolidated rock to the lowest possible limit, deposition is ever working to steal material from erosion in order to start rebuilding. Ultimately deposition gains all the waste of erosion, since at the meeting place of land and ocean surface forces of degradation are rendered practically impotent. It is here that the main work of surface reconstruction is accomplished.

For convenience of discussion deposits of rock débris may be classified as *continental*, those laid down on the land before reaching the sea, and *marine*, those deposited in the sea. It must be remembered, however, that when the sea encroaches upon the land, continental deposits are reworked by the waves so as to look like marine deposits. Then, too, continental deposits are ever open to new attack by erosive agencies, so that their status in any classification is not very secure.

CONTINENTAL DEPOSITS

Production of mantle rock. All the mechanical and chemical instruments of surface destruction work toward the production of loose, minutely divided particles of rocky material. Much more of this waste is developed than can be removed to the sea; so it lies as a mantle over the consolidated rock of the earth's skeleton. In some places this mantle rock remains as a residuum of decay of the parent rock directly below; in other cases it has been transported by wind or water from far-distant regions. In most places the mantle rock is made up of the disintegration products of rocks more or less highly varied as to mineral content. Topographic and climatic conditions which control the thickness of the mantle present such a wide range of variability that the surface covering of loose material may be from a few inches to hundreds of feet deep. The surface portion of the mantle rock, commonly called *soil*, is usually made up of very small mineral or rock particles. At the surface the scarifying action of weather and erosion is greatest, tending to remove the large particles or reduce them to smaller and smaller fragments. Soil is the home of vegetation, and the roots of plants aid the agents of weather in reducing the surface mantle to ever smaller particles. Soils are as diverse in their characteristics as are races of people, and have played no insignificant rôle in civilization. Wheat fields in Minnesota, tobacco in Virginia, and blue grass in Kentucky are the logical results of peculiar soil and climatic conditions, as are the cactus plains of Arizona as well as the sagebrush wastes of Wyoming. Almost without an exception man's prosperity is contingent on the ability of the soil on which he lives to produce the vegetation that is needed by him or his domesticated animals.

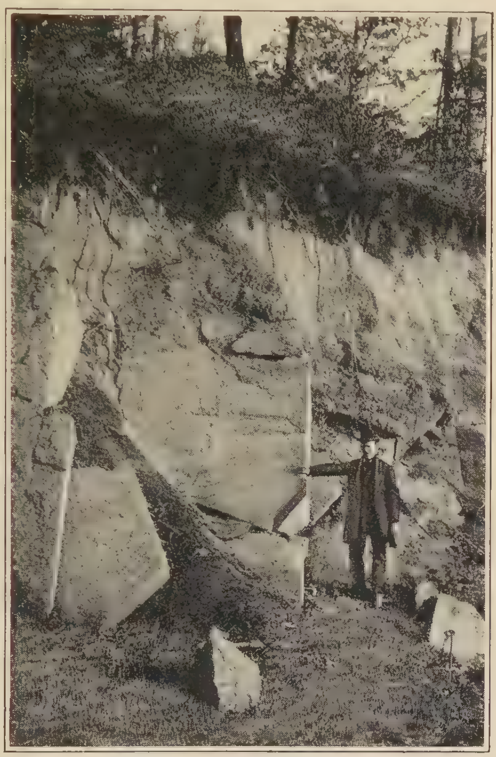

FIG. 60. Granite disintegrating to produce mantle rock. (Courtesy of Dr. G. P. Merrill and the Geological Society of America)

Notice the gradation from the consolidated granite through the subsoil into the soil, which is darkened by the decay of plants

In wet climates the soil grades downward into differently constituted *subsoil,* which has less organic matter than the true soil above and which is apt to differ somewhat in its mineral make-up because it is less exposed to oxidizing and hydrating agencies. For these reasons the subsoil is not so fertile as the true soil. For many centuries man has used the soil and considered it an inexhaustible resource. It is true that growing vegetation takes from the soil certain salts necessary to prolonged agricultural exploitation, but the ingenuity of man has devised artificial means, such as crop rotation and fertilization, to restore these invaluable ingredients. It is only recently that thoughtful farmers have begun to suspect that under long development the actual physical body of the soil is reduced. Deforestation, always an accompaniment of agriculture, and the yearly plowing of fields make the farm an easy victim of erosion. Some idea of the toll taken can be had when the muddy waters of most rivers in spring flood are considered. Much of this mud was derived from the easily removed surface of arable land. Will the processes of rock weathering be able to keep pace with the rapid removal of soil by rain, wind, and river, supplying new soil rich enough for agricultural purposes, or will the land be gradually denuded so that the soil will be too thin or too infertile for successful farming? A partial answer to this question may exist in the present condition of the ancient farm lands of south-central China and elsewhere, the fertile soil of which has been notably reduced by erosion at times of river flooding, so that crops are gradually growing poorer.

The mantle rock covering most of the lands of the earth is produced largely by the slow decay of consolidated rock under the attack of chemical agencies. In places, however, the mantle was clearly produced by the mechanical action of weather, with frost as the important instrument. We have seen how cliffs are broken down by frost action and how talus accumulations of the angular, unassorted rock fragments gather in mountainous regions. Sometimes such accumulations may spread over large areas and become cemented by silica or calcium carbonate carried by percolating rain water. When talus deposits become cemented they no longer constitute part of the mantle rock, but become a new rock type called a *breccia.* Breccias are constructional rock bodies made from the mechanical destruction of former rocks. They are characterized by the angular, nonrounded fragments out of which they are made.

Wind-laid deposits. We have observed how the wind wears rocky surfaces by sand-blasting them with loose material picked up from the mantle rock. Inasmuch as the wind is fickle and may abrade and deflate an area temporarily, it will surely tire of destruction and will dispassionately drop the materials which for a time it assiduously garnered. The work of the wind is never finished, for after a deposit is made the restless air may straightway set out to destroy it. Thus the deposits of this type are transitory phenomena, and as such are among the most interesting and often vexing problems in surficial geology.

Dust. Dust is a universal deposit of the wind. Everywhere it is dropping out of the atmosphere, but only after being carried long distances by the wind. Much dust is wafted from the mouths of fuming volcanoes, but some is gained from other sources. All agencies which produce fine particles of rock, as well as microscopic plants and animals, contribute to the ubiquitous dust of the earth's surface. Sometimes the rain brings dust from the atmosphere to the surface of the earth. The "blood rains" of France are caused by the coloration of rain by fine particles of red rock drifted northward on the wind from the deserts of Arabia and Africa. Sometimes dust abandoned by the wind falls slowly to earth by virtue of its weight, which is slightly greater than that of the air.

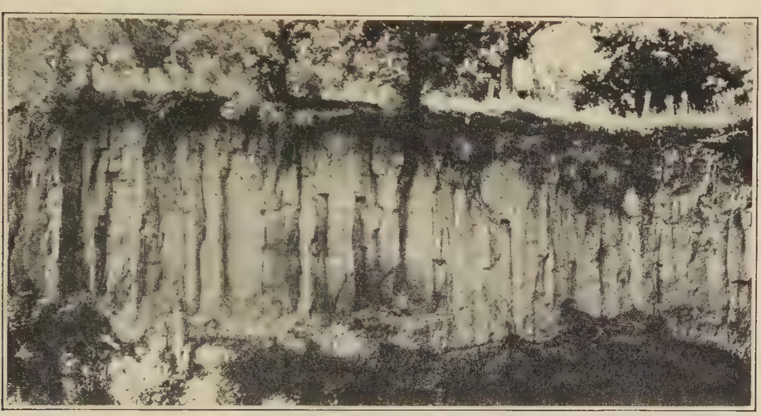

FIG. 61. A bank of loess. (Courtesy of the United States Geological Survey)

Although dust is always falling on the earth, there is no gauge as yet devised to measure the annual precipitation.

That the results of long ages of dust accumulations may be great is evidenced by the thick deposits of *loess*, which is believed to be a wind-blown accumulation of dust (Fig. 61). Loess is finely divided rock material covering large areas in China, North America, and elsewhere. In China loess deposits attain to a thousand feet in thickness over broad areas and must have required a vastly long time, together with essentially uniform atmospheric conditions, for their deposition.

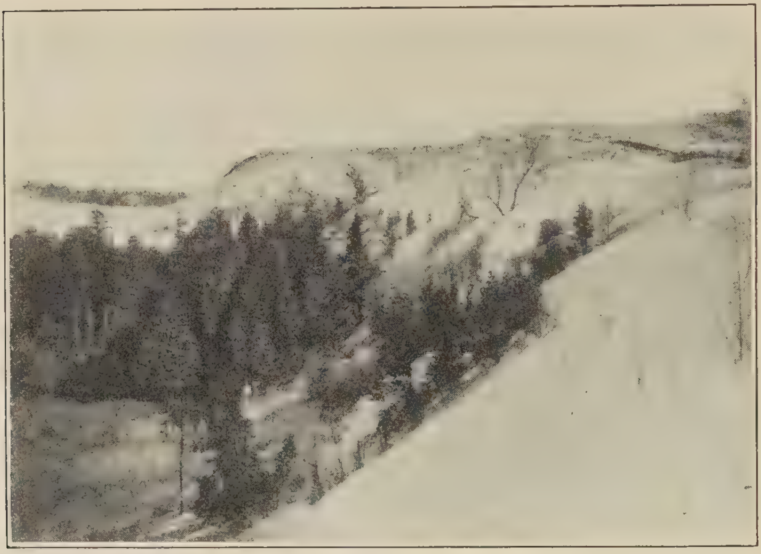

FIG. 62. Sand dunes on the south shore of Lake Michigan. (Courtesy of the United States Geological Survey)

Sand. Sand, unlike dust, is not commonly lifted far above the surface of the land. Its movement is therefore controlled by the obstacles which it meets. Whereas dust is usually dropped uniformly over the earth's surface, sand is commonly heaped up in the shape of mounds called *dunes* (Fig. 62). Dunes may be elongated in the direction of the prevailing wind as short or long ridges, straight or curved, or they may be round and hill-like. In some cases heavily loaded winds deposit sand which forms dunes transverse to the direction along which the wind blows. Dunes are normally low, but occasionally giants of three hundred feet or more are formed.

Dunes are started by the lodgment of loose, dry sand around an obstacle such as a tree stump, a bush, or a bowlder. Their favorite haunts are along sandy shores of rivers, lakes, and sea, but they form anywhere that the wind rolls sand grains along until an obstacle is encountered. Here the dune begins, and continues growing as long as the wind is able to feed it. The windward side of a dune has a gentle slope terminated by a crest beyond which, on the lee side, the declivity is more abrupt. The dune gains in size to a certain point, depending on the average intensity of the prevailing winds. Beyond the crest, where the strength of the wind is checked, the sand is dropped and left to lie at the steepest angle possible for material of this size, this angle never exceeding 30°.

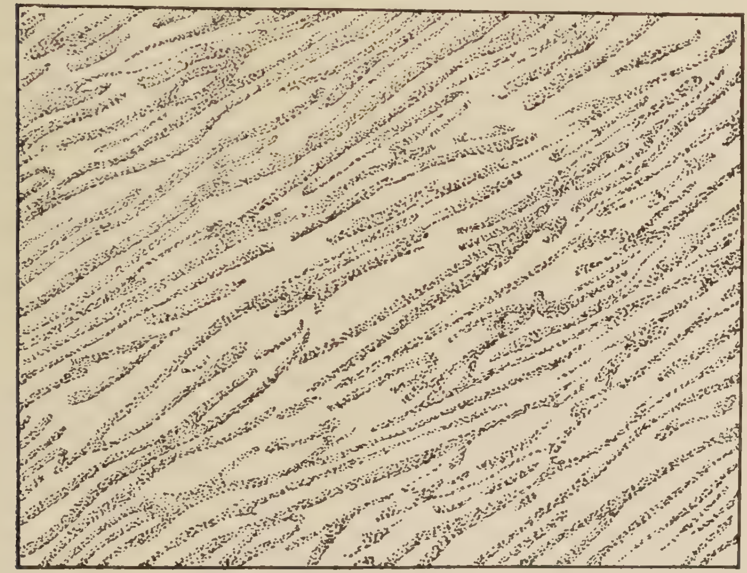

FIG. 63 A. Dune ridges parallel to the direction of the wind, formed by strong winds acting upon a large supply of sand. (After Cornish. Reprinted by permission from "Geology," by T. C. Chamberlin and R. D. Salisbury. Published by Henry Holt and Company)

The steady rolling of sand up the gentle windward slope, to be dropped on the leeward side, causes dunes to creep slowly in the direction of the prevailing wind. Sand moving in this way brings death to all types of vegetation and has even been known to bury entire cities. In central Asia explorers have discovered the remains of ancient civilizations partly laid bare of the sand which had buried them centuries ago. On the north coast of Germany a huge dune was observed during a period of sixty years. In that time it advanced upon a church, overwhelmed it, and then marched on. Dunes near inhabited areas have often proved themselves a menace, and man has attempted to anchor them by starting a growth of timber on their backs. This has been successfully done in France and on the Pacific coast of North America. Sometimes sand dunes die a natural death by being rendered stationary by the vege-

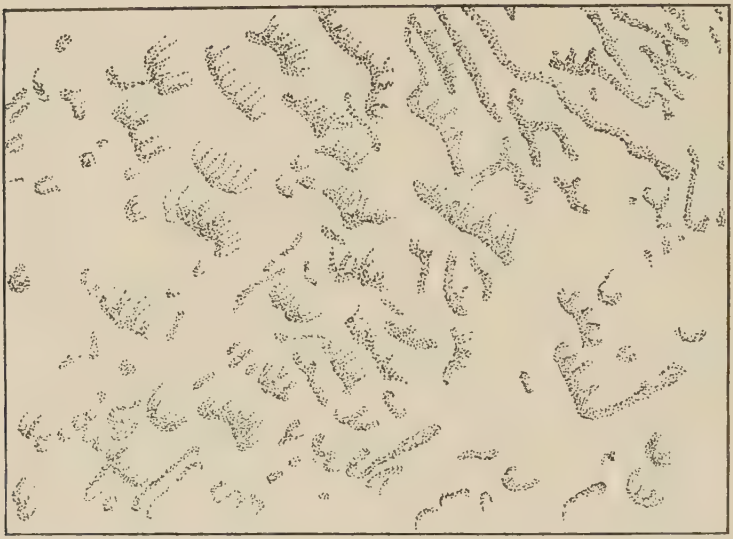

FIG. 63 B. Dune ridges transverse to the direction of the wind, formed by moderate winds acting upon a large supply of sand. (After Cornish. Reprinted by permission from "Geology," by T. C. Chamberlin and R. D. Salisbury. Published by Henry Holt and Company)

The wind is from the southwest

tation which is ever striving for foothold in sandy places. Such inactive dunes are those on the south shore of Lake Michigan.

Constructive work of ground water. Enough has already been said to show that while destruction is the overpowering tendency of surface agencies, some constructive work in the form of deposition is accomplished on the land surface. Just below the surface, however, and above that irregular line which marks the upper limit of the underground water is a zone wherein destructive processes gain tremendously over reconstructive processes. From this so-called *zone of weathering*, materials are constantly being leached out by percolating rain water and carried into the body of the ground-water circulation. Although this circulation is destructive to the rocks through which it moves, it is likewise constructive, since the ground water is just as likely to deposit some of its dissolved burden of mineral matter as to add to it. The chemical magic of ground water makes a story both interesting and varied. Certain rock bodies are known to have been completely altered by its transforming touch, their original minerals being carried

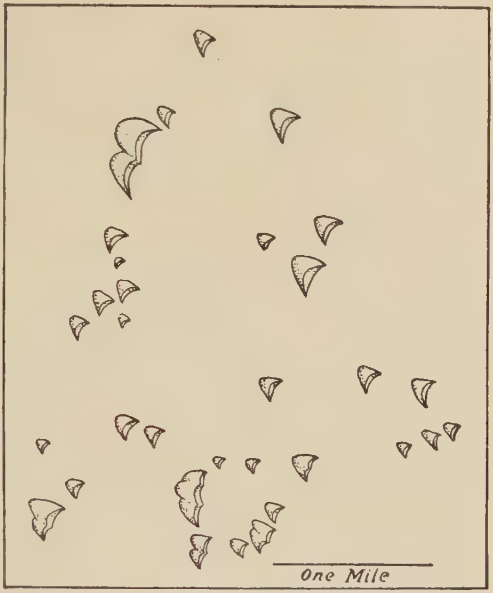

FIG. 63 C. Crescent-shaped dunes, formed by moderate winds acting upon a moderate supply of sand. (Reprinted by permission from "Geology," by T. C. Chamberlin and R. D. Salisbury. Published by Henry Holt and Company)

The wind is from the northwest

away and replaced by others of a totally different nature. Some of the rare and precious minerals have been concentrated by ground waters in this way so as to form rich deposits available to the use of man. Geologists sometimes refer to the *zone of cementation,* where ground water deposits more mineral matter than it dissolves. Many variable factors are to be considered before such a zone can be definitely located; it must necessarily vary from place to place, and in some cases be totally absent.

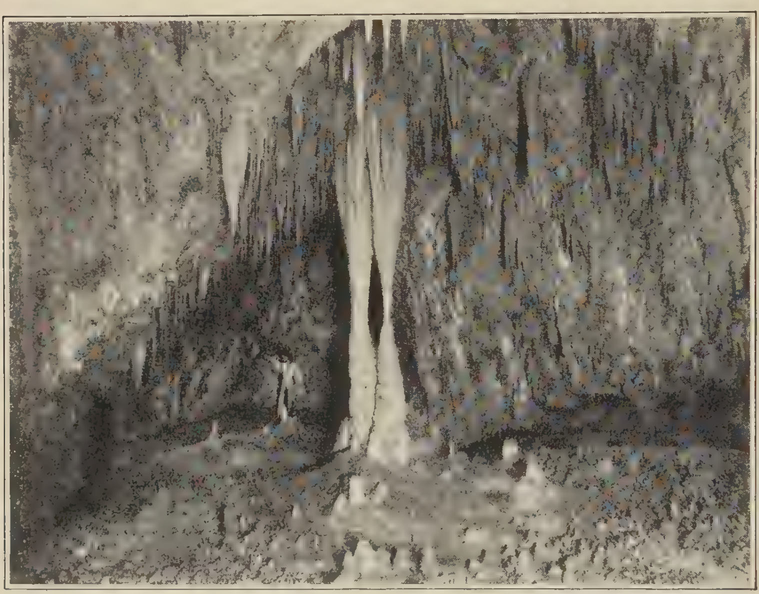

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FIG. 64. The interior of a cave showing stalactites, stalagmites, and a double column. (Reproduced by special permission of the *National Geographic Magazine*)

Caves. Ground water depositing minerals in caves creates some of the most beautiful effects in nature. The normal tendency for ground water which has excavated caves in limestone rock is partly to refill the cavities it has made. Beautiful *stalactites* resembling icicles are formed from water charged with calcium carbonate leaking through the roofs of caverns (Fig. 64). The carbon-dioxide gas slowly escapes from the dripping water by evaporation, leaving behind a deposit of lime. Such water falling on the floor of a cave forms *stalagmites* in a similar manner (Fig. 64). In some cases stalactite unites with stalagmite to form a *column*. Many strange rock forms are produced by lime-charged waters dripping from roofs of caverns, so that the effect may be that of a Gothic cathedral with graceful fluted columns and delicate traceries, or a weird room peopled with Gargantuan toadstools and travesties of wild beasts.

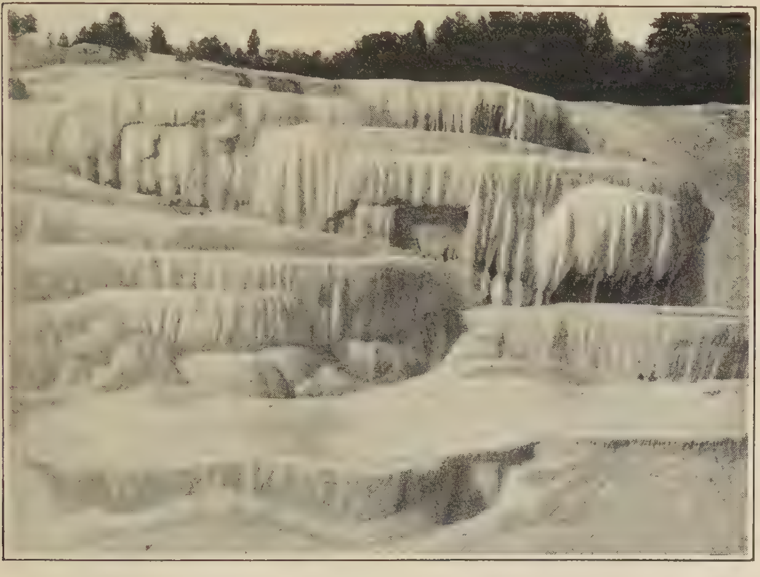

FIG. 65. Terraces of the Mammoth Hot Springs in Yellowstone National Park

Springs. In its slow and devious way to the sea, under ground water may emerge to issue in the open as springs. When the air is reached, evaporation is stimulated; if the waters are charged with much mineral matter, deposition is the usual result. Some springs build up mounds and terraces, often of rare beauty, around their vents. One of the most beautiful of these formations is the Mammoth Hot Springs in Yellowstone Park (Fig. 65).

A spectacular but unimportant type of ground-water deposition can be observed at the mouths of the eruptive hot springs known as *geysers*. Silica, the substance of which glass is made, is plentifully deposited around the orifices of the geysers in Yellowstone Park, sometimes in the form of a craterlike basin and sometimes in the shape of a cone. In many cases hot-spring and geyser deposits are exquisitely colored by iron and by tiny plant organisms which live in the steaming waters.

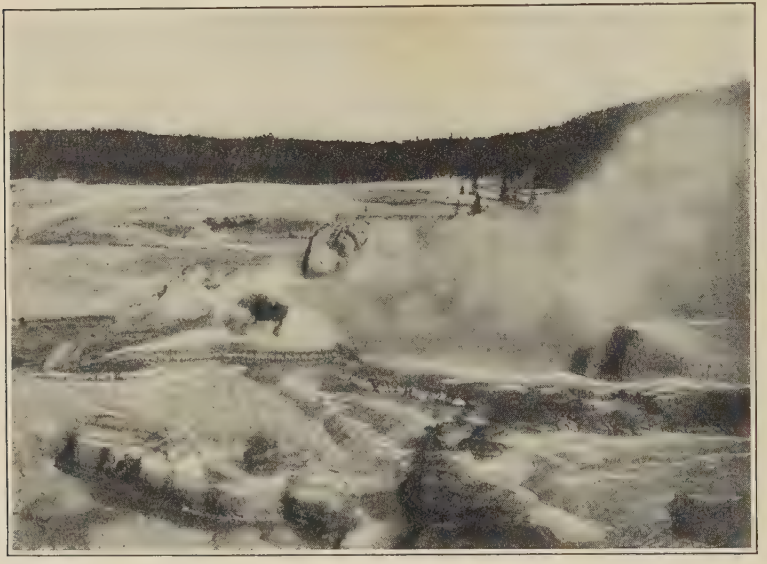

FIG. 66. Siliceous deposits around the orifice of Old Faithful geyser, Yellowstone National Park

River-laid deposits. Along the upper reaches of streams, where gradients are steep, little constructive work is accomplished. Before they reach the sea most streams must traverse lowlands, where the velocity of the water is slackened, so that some of the suspended load is dropped. It is the rule rather than the exception that streams should be eroding in parts of their valleys while depositing in others.

Alluvial cones, fans, and plains. Where rivers flow down the slopes of hills, ridges, or mountains, or where a rapidly flowing tributary stream enters the valley of a more slowly moving river, velocity is checked where the gradient is lessened, so that a large part of the rocky burden of the stream may be deposited. If the stream's velocity is checked abruptly, as in the case of a mountain stream issuing from a ravine, the deposit made will be an *alluvial cone*, closely resembling a talus cone.

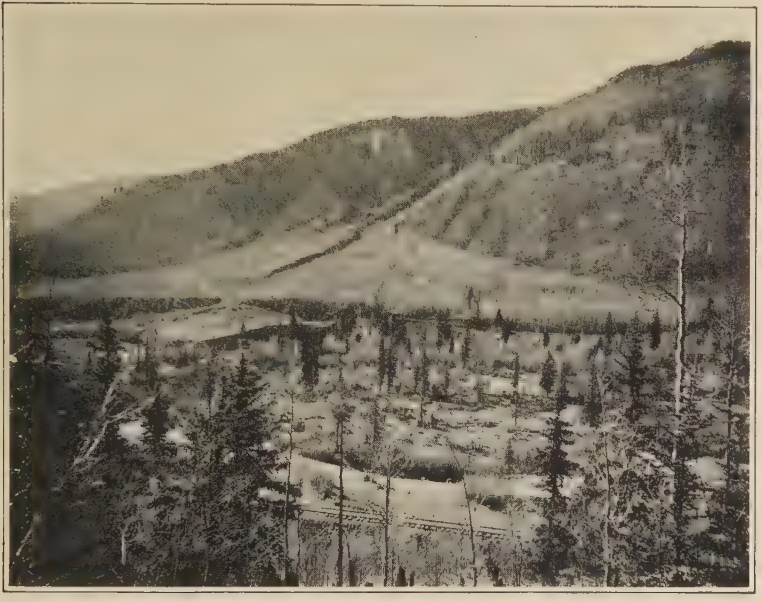

FIG. 67. An alluvial fan. (Courtesy of the United States Geological Survey)

If the velocity is diminished more gradually, the slope of the deposit will be more gentle, flaring out in the shape of a partly opened fan, an *alluvial fan* (Fig. 67). Alluvial cones and fans terminate many intermittent streams which flow from wooded mountains upon dry, sandy plains. Where the checking of the river's velocity is very gradual, alluvial material may be spread for miles over the valley as an *alluvial plain*. Related to these types of deposits are the *sand bars* which form in rivers that are depositing sediment in their channels. Pilots along the lower Mississippi know well the treacherously shifty nature of sand bars, and keep vigilant watch for them in time of low water.

Flood plains. People who live along the lower courses of great rivers know that spring floods are an annual occurrence. Such floods are the results of the accumulative effect of many April showers united with the melted snow of winter. Where swollen rivers flow over lowlands, as they do, in most cases, in their lower reaches, the water overflows its banks to spread widely over the adjacent lowlands. With such widening of the stream the velocity of the turbulent water is checked, and the burden of fine mud is deposited on the land. Such a surface of deposition is known as a *flood plain.* When the water creeps back within its channel, the mud is left behind. Where the stream leaves its banks, deposition is greatest, because at this point a marked lowering in velocity occurs. Here the stream tends to build up low ridges (*levees*), which sometimes become high enough to prevent disastrous flooding. Taking their cue from nature, men inhabiting such valleys have artificially built up natural levees in an attempt to check the inroads of the water on their homes and fields. At times these levees break, allowing the surging waters to spread frightful ruin and destruction.

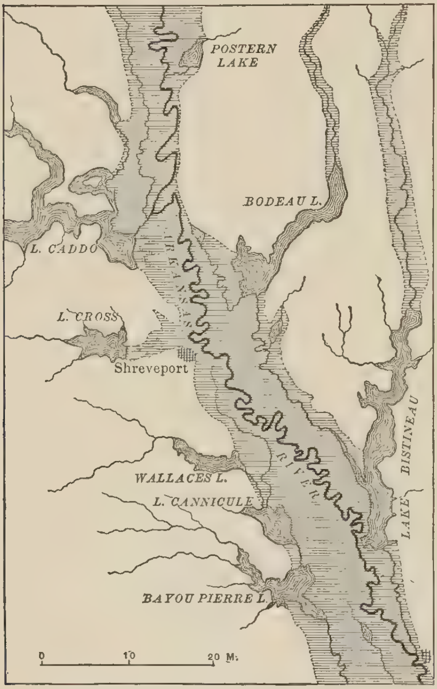

FIG. 68. The flood plain of the Red River, Louisiana. (From Davis's "Physical Geography")

A river flowing over a flood plain almost never follows a straight course. A river's banks are always less resistant in some places than at others, so that the stream cuts in where cutting is easiest. Then, too, a gently flowing stream is easily deflected by an obstacle such as a large rock, with the result that it is continually being thrown out of its course. When curves are once started in a river, the main current is directed into them so as to increase the curvature rather than reduce it. The water issuing from such a curve is thrown against the opposite bank, and here another curve tends to develop. When such curves, or *meanders*, are once started, they become more and more pronounced, and the land between each two adjoining curves becomes gradually narrower, until at some point the river cuts through as shown in Fig. 69. When this happens, the stream takes the shortest course, and abandons the wide curve of its former channel. With time both entrances to the former channel become clogged with silt and are cut off from the river. Such a loop-shaped body of standing water is called an *oxbow lake* (Fig. 70). The ultimate fate of oxbow lakes is to become filled with sediment and changed into marshes.

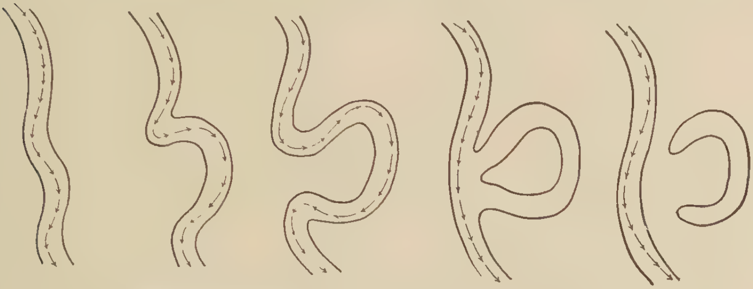

FIG. 69. Diagram showing the origin of meanders and oxbow lakes

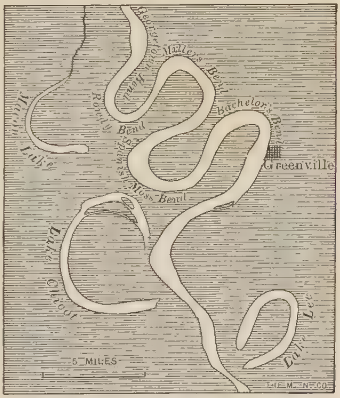

FIG. 70. Meanders and oxbow lakes of the Mississippi River. (From Davis's "Physical Geography")

Streams meandering over flood plains have little to check their lateral lashing until they impinge against the steeper walls on either side of their broad valleys. Here the work of destruction is taken up anew, and the valley is widened. This process, known as *lateral planation,* is characteristic of all old rivers flowing in broad valleys. When a river is undermining and cutting down its bank on one side, deposition is usually taking place on the other side of the channel at the same point. A little lower down the channel there is usually a point where the two processes change sides, so that as one goes along a bank of the river one comes alternately to a spot where the bank underfoot is being eroded and to a spot where the bank is receiving deposits. In a similar way, when a stream in flood is building up its flood plain by deposition, it is normally degrading its main channel by erosion.

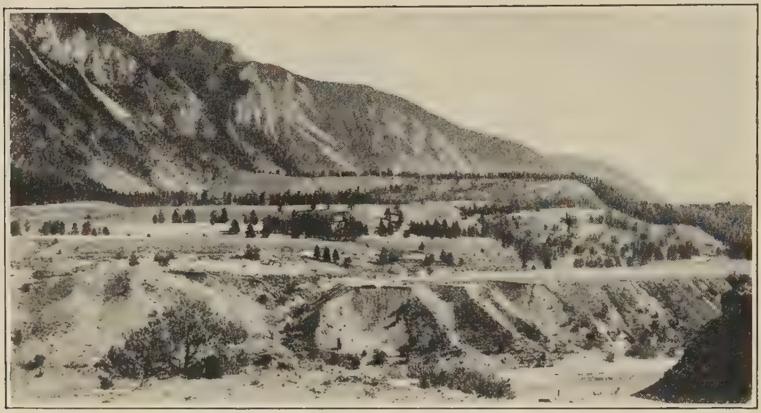

FIG. 71. Terraces of the Fraser River, British Columbia. (Photograph by A. M. Bateman. Courtesy of the Geological Survey of Canada)

Terraces. Along some rivers long, narrow, benchlike plains, or *terraces*, are built up from material which is being transported (Fig. 71). Such terraces may be the vestiges of former flood plains, almost destroyed when uplift of the land stimulated the stream to renewed erosive energy. Although terraces are formed in a variety of other ways, they usually stand as reminders of a former time when the river was actively depositing its load before the ultimate destination, the sea, was reached. Sometimes in the history of rivers successive uplift seized the land, with the result that successive flood plains were developed and then partly removed by the stream. It is not uncommon to see remnants of these ancient flood plains in the form of terraces, perched at different levels along the valley sides, giving clear evidence of the alternate periods of downcutting and uplifting along the river's course.

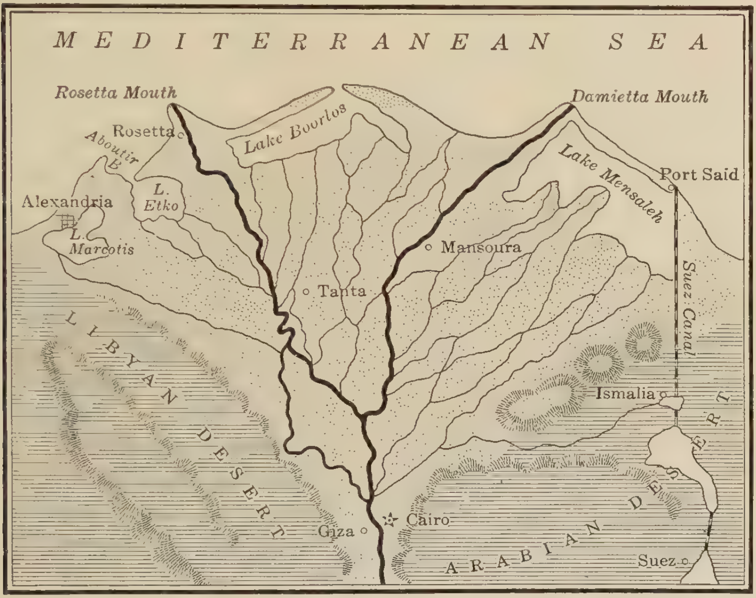

FIG. 72. The Nile delta, showing distributaries. (Reprinted by permission from "Textbook of Geology," by L. V. Pirsson and C. Schuchert. Published by John Wiley & Sons, Inc.)

Deltas. What remains of a river's burden when it enters standing water, whether sea or lake, or even a more slowly moving stream, is deposited in a highly characteristic river deposit called a *delta,* so named because of the triangular shape similar to the Greek letter delta (Fig. 72). When even the strongest stream flows into a body of standing water, its velocity is checked, so that it is rendered powerless to carry sediment. This weakening of rivers at their mouths causes the deposition of material carried in suspension as well as that rolled along the bottom. Under suitable conditions great deposits are built up, as time goes on, until new land is formed where once was the river's mouth. Across this new land the river laboriously works its way, usually breaking up into branches roughly similar to the ribs of a fan. These *distributaries* build out the deposit laterally, giving to the delta its triangular shape. The height of deltas is greatly built up by the rivers when in flood, so that the bulk of the deposit may be above water when the stream is in normal stage. Distributaries of a river flowing over their delta preserve channels for themselves by building up levees. Since the tendency of a river is to thwart its own purpose of getting into the standing water beyond, it frequently dams up its outlets by deposition, so that levees are broken and new distributaries cut. As a river creeps over the dam which it builds in its own path, the fine mud in suspension is carried farthest and dropped in front of the advancing delta. As time goes on, and

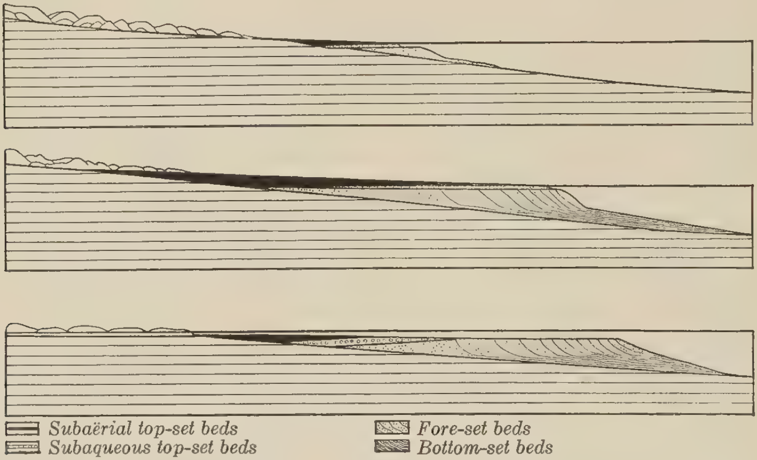

FIG. 73. Diagram showing the stages in the formation of a delta. (Modified from J. Barrell)

the delta proper moves forward, this advance guard of sedimentation (*bottom-set beds*) is buried under the coarser material, which is rolled along the bottom of the river channel and dumped over the steeply sloping front of the growing delta (*fore-set beds*). The fore-set beds normally have a steep seaward inclination. With time the earlier formed bottom-set beds become covered by the inclined fore-set beds deposited at a later time. A residuum of sediment may still be left in the water of the river; this residuum is deposited, especially in flood times, on top of the fore-set beds (*top-set beds*). The top-set beds, like the bottom-set, are essentially horizontal, and complete the threefold structure of the typical delta (Fig. 73).

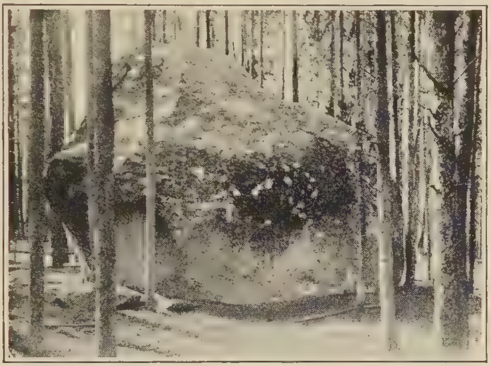

FIG. 74. A glacial erratic in Glacier National Park. (Courtesy of the United States Geological Survey)

The greatest enemies of delta growth are the tides, waves, and currents in the sea, which conspire to sweep the river-deposited material away as fast as it is laid down. Sometimes the forces of the sea succeed in preventing the accumulation of a delta, as in the case of the Thames in England. Sometimes, however, the river triumphs, as in the cases of the great deltas built into the ocean by the Niger and the Ganges. The most successful deltas are formed by rivers emptying into lakes or protected seas; such are the Danube and the Mississippi.

With prolonged deposition at its mouth, a river may build up land areas of considerable extent. The Mississippi delta is over 200 miles long, and its area is over 12,000 square miles. The combined deltas of the Ganges and Brahmaputra cover an area of probably more than 50,000 square miles. The delta of the Nile is approximately 200 miles wide to seaward and extends nearly 100 miles from shore.

Deposition by moving ice. The rock débris heaped up by glaciers falls into two natural groups: (1) material which is deposited directly by the ice and (2) material which is deposited beneath the glacier by streams flowing within the ice or in front of the glacier by streams issuing from it.

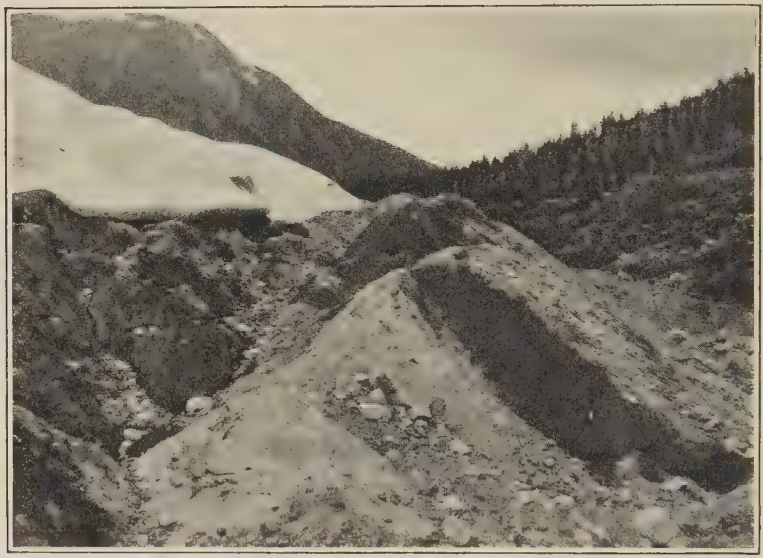

FIG. 75. A terminal moraine in the process of formation at the front of an Alaskan glacier

Ice-laid deposits. When a glacier disappears by melting, all its rocky burden is deposited. Because of the nature of gathering and transportation, the drift scattered over the country by moving ice is typically unassorted and unstratified, often made up of poorly rounded, subangular fragments. After the ice retreats, a country which has been covered widely by glacial ice of continental proportions is likely to be burdened with a scattered covering of rock débris of all sizes and shapes and differing in mineral make-up from the bedrock underneath. In places great blocks of rock as large as houses have been carried long distances on the back of the moving ice, to be dropped finally in a region whose bedrock may be of a totally different nature. Such wandering giants and their smaller brethren are known as glacial *erratics,* because they have come to places where they stand as anomalies, foreigners in a new country. Sometimes the parent ledge from which such wanderers took rise can be discovered, and then it is easy to determine how far they have been transported; more often they stand alone as misplaced, "lost" rocks. From study of such "lost" rocks Louis Agassiz first built up the theory of their explanation by glacial transportation, a theory which has long since been established as a fact through the combined evidence discovered by many other careful observers.

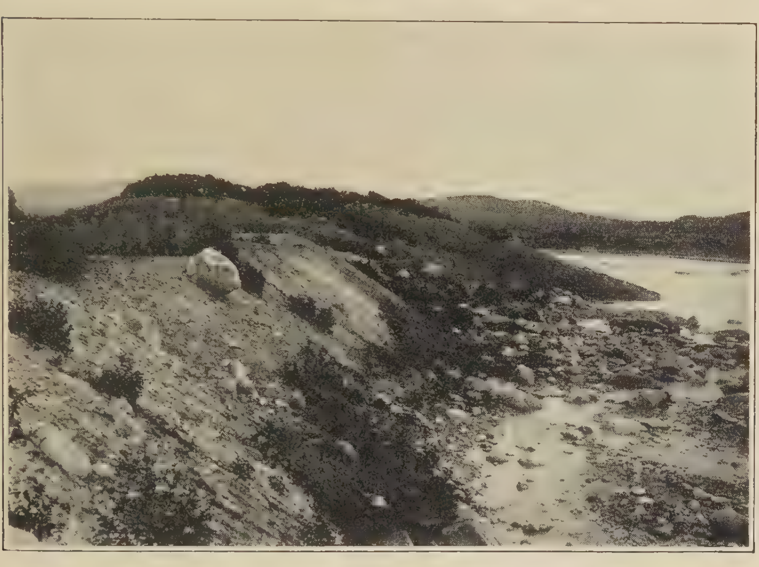

FIG. 76. A lateral moraine, Mendenhall glacier, Alaska

With the larger erratics, continental ice caps deposit much smaller material. In many cases this material consists of gravels, sands, and clays of varied mineral make-up, deposited, without any special arrangement, as a film of loose débris over wide areas. Such material, as we have seen, goes by the inclusive title of glacial drift. Sometimes, however, moving ice arranges its deposits in characteristic mounds and ridges called *moraines*. These deposits differ strikingly from water-laid deposits in their jumbled, unassorted, always unstratified arrangement. Many of the stones are apt to be scratched or polished; others have flat surfaces, or facets, produced upon them by the grinding action of the moving ice. Such well-marked pebbles must have been derived from rock at the bottom of the glacier, either carried by the ice and scraped along bedrock or part of the scarified bedrock itself, plucked out and worn by the ice.

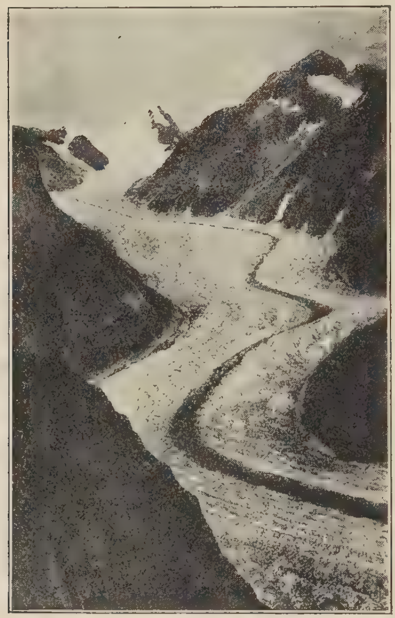

FIG. 77. A medial moraine on the Fiesch glacier, Switzerland. (Reprinted by permission from "General Science," by W. H. Snyder. Published by Allyn & Bacon)

At the end of a glacier (if it is of the mountain or the valley type) and at the margin of continental ice sheets, débris is heaped up in *terminal moraines* (Fig. 75). The longer the ice front is stationary, the greater will be the accumulation at its terminus. A moving river of ice gouging deeply into its steep-walled mountain valley gathers much rocky material along its sides, which piles up into ridges called *lateral moraines* (Fig. 76). Where tributary glaciers join their mains, the lateral moraine of the tributary joins that of the main glacier, forming a *medial moraine* on the back of the main glacier below the mouth of the tributary (Fig. 77). Material carried along the bottom of a glacier is called the *ground moraine*. Moraines sometimes attain to large proportions.

Lateral moraines on living glaciers in the Italian Alps are said to be over a thousand feet high, although fifty to a hundred feet would be more nearly the average.

Moraines are always composed of unassorted material called *till* (Fig. 78). After the ice has disappeared, it is possible in many cases to define clearly the heaps of morainal material once slowly moved in the direction of ice advance.

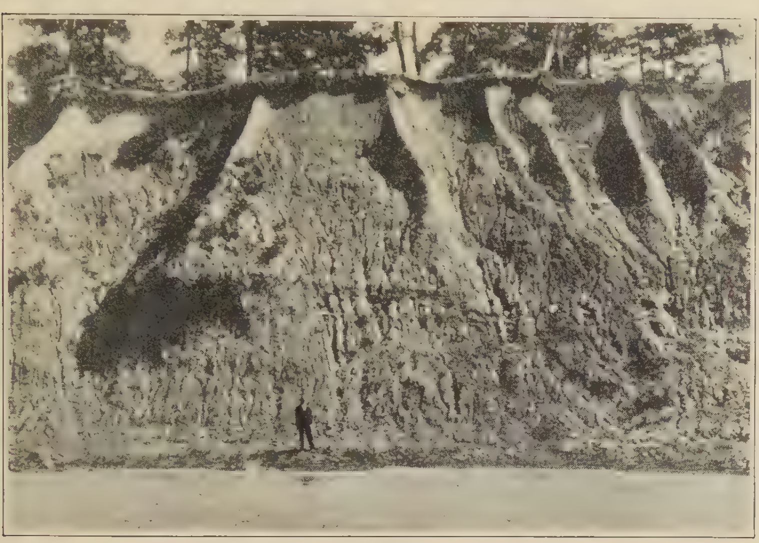

FIG. 78. A bank of glacial till, Ohio. (Courtesy of the United States Geological Survey)

During the Pleistocene period North America and the other continents of the Northern Hemisphere felt the coming and going of several ice caps. Where the fronts of these great continental glaciers were stationary for a time, terminal moraines were left standing to record the fact. The ground moraine of such ice sheets was in some places built up into elongated cigar-shaped hills of till, sometimes as high as three hundred feet. They are common in eastern Wisconsin, in central New York, and in the vicinity of Boston. If one stands on a prominence south of Boston and looks northward, groups of *drumlins* can be seen, all elongated in a general north-south line — mileposts that mark the direction of movement of the ancient ice cap (Fig. 79).

Water-laid deposits. The streams which are the offspring of all glaciers are always overburdened with an inheritance of sediment from the mother ice. Usually the fine mud in such streams is light-colored, giving a characteristic milky appearance to the water. Unlike a normal river, which uses some choice in the matter of gathering its load, glacial streams almost always are given at birth far heavier burdens than they can carry. As a result, deposition takes place very near the front of the ice, and the abnormal phenomenon of a flood plain at the very source of a river is not infrequently produced. Such alluvial plains sloping down the valley from a terminal moraine are called *valley trains.*

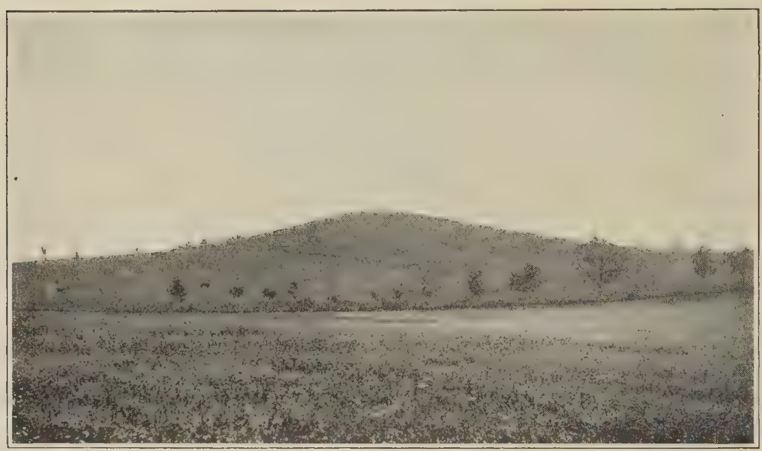

FIG. 79. A drumlin in Wisconsin. (Photograph by W. C. Alden. Courtesy of the United States Geological Survey)

In continental glaciers, where not one but many streams issue from the broad ice face, the single valley train typical of mountain glaciers is represented by a broad, widely spread sheet of débris fringing the ice front as an apron. This is called an *outwash plain.* Such deposits differ from the ice-laid moraines in being more or less stratified, after the custom of all stream-laid deposits. Some degree of rounding and sorting of grains and pebbles is usually accomplished, although the overworked glacial streams must deposit much of their load before it can be worn to the likeness of typical river material.

Two types of glaciofluvial deposits merit special description: *kames* and *eskers*. Kames are born near the front of a retreating ice cap. They resemble drumlins except that their

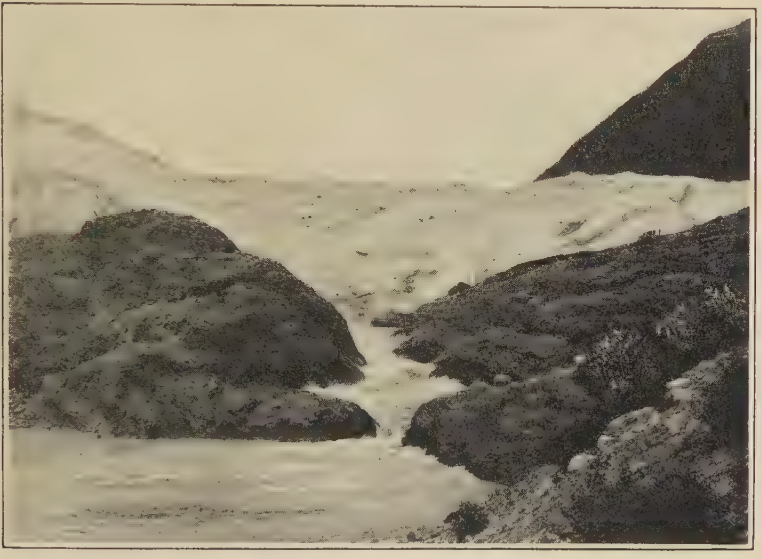

FIG. 80. Birth of a glacial stream at the front of an Alaskan glacier

material is stratified and their alignment is perpendicular rather than parallel to the direction of ice flow (Fig. 81). It is thought that kames are formed by subglacial streams dumping sediment in depressions along the irregular margin of the ice sheet. After the ice has melted, these peculiar knobs of drift are left standing as protuberances. Eskers are serpentine ridges of stratified sand and gravel thought to have been formed by streams flowing either on the ice or through tunnels within the ice. Because of the confining nature of such stream channels the material is heaped up in long, steep-sided ridges, which stand out conspicuously after the ice has melted away (Fig. 82). Eskers are usually under forty feet in height, but sometimes they attain to the height of a hundred feet. In Finland and in some places in the Scandinavian Peninsula eskers many miles in length are known.

Lake deposits. Deposition in lakes has many similarities to that in oceans, since lakes, like oceans, are bodies of standing water which receive sediment from streams and from the wear of the land by their waves. On account of the lethargic nature of lakes little sediment brought into them ever escapes, and for this reason lakes are and have been important areas of constructive geological work on all continents. Because of this fact the fate of most lakes is early extinction, either through sapping by rivers or by being filled up with sediment. Lakes are of two distinct types: *fresh-water* and *saline*. The former are characterized by a preponderance of mechanical deposition over chemical deposition; in the latter the reverse is true. Old lakes, long ago filled with sediments, are common phenomena, and in some cases show beautifully preserved deltas which former rivers, unharassed by currents and tides, had built far out into the body of the depression. Sometimes microscopic plant organisms (*diatoms*), which build exquisite

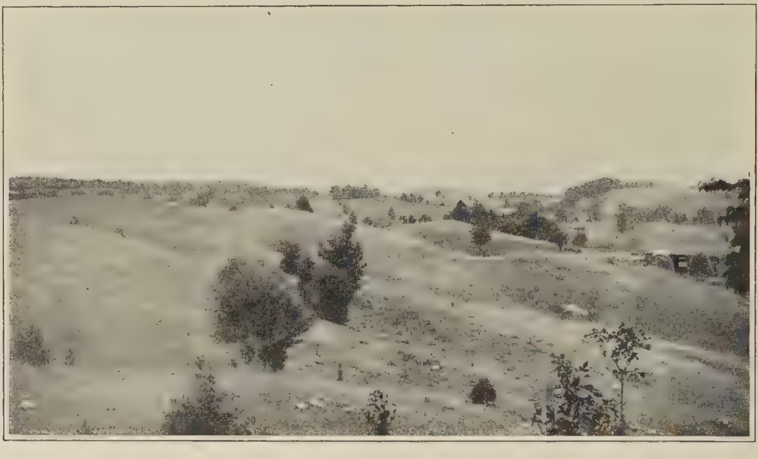

FIG. 81. Kames in New York. (Courtesy of the United States Geological Survey)

skeletons of glass from the silica in the water, aid materially in the filling up of lakes. In places deposits of considerable extent are amassed by the limy shells of fresh-water clams and snails.

In arid countries saline lakes whose waters are rich in the salts of various chemical substances are not uncommonly developed, because the excess of evaporation over rainfall removes much water from the lake and concentrates the mineral matter in the remainder, often in rather strong solutions. Salt lakes may have descended from fresh lakes in regions where the climate has gradually grown drier. Others are formed when arms of the sea are cut off from the open ocean, allowing evaporation to exceed inflow and thus concentrating the mineral substance native to all land waters. The mechanical deposits in saline lakes resemble those of their fresh-water cousins. Their chemical deposits, however, are unique and in some cases of great value to man. After concentration has

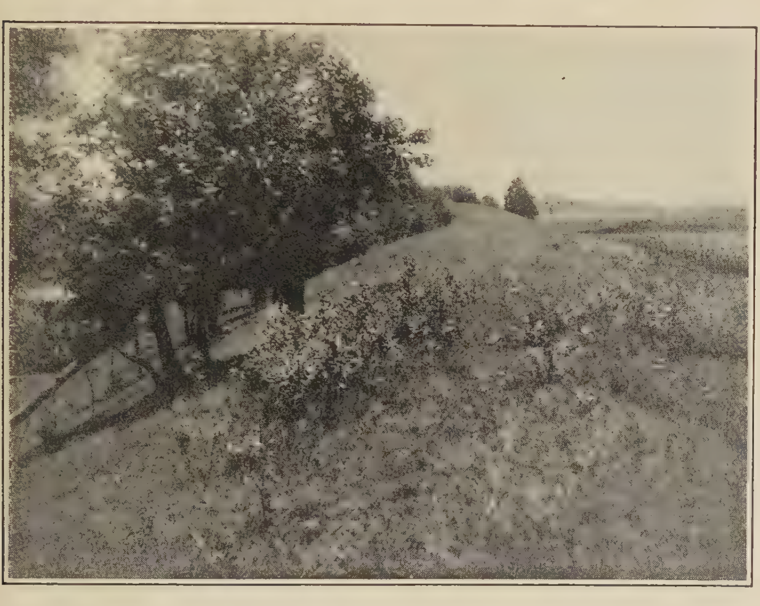

FIG. 82. An esker in Minnesota. (Courtesy of Dr. R. T. Chamberlin)

continued to a certain point in a lake, the water cannot hold all its dissolved load and begins depositing, first the least soluble substances and gradually, with further concentration, the more soluble constituents. Lime carbonate and iron oxide are the first to be deposited in this sequence. In Pyramid Lake, Nevada, a remnant of the great extinct Lake Lahontan, curiously shaped islands of domelike calcareous rock (*tufa*) are to be seen as the result of precipitation aided by small organisms in a lake where the saturation point for calcium carbonate had been overstepped (Fig. 83). After further concentration lake water gives up its calcium sulphate in the form of gypsum, a mineral popularly known as the chief ingredient in plaster of Paris. The more easily soluble salts, such as sodium chloride (common table salt) and magnesium sulphate, do not form until evaporation has continued much further. The most highly soluble chlorides of magnesium and

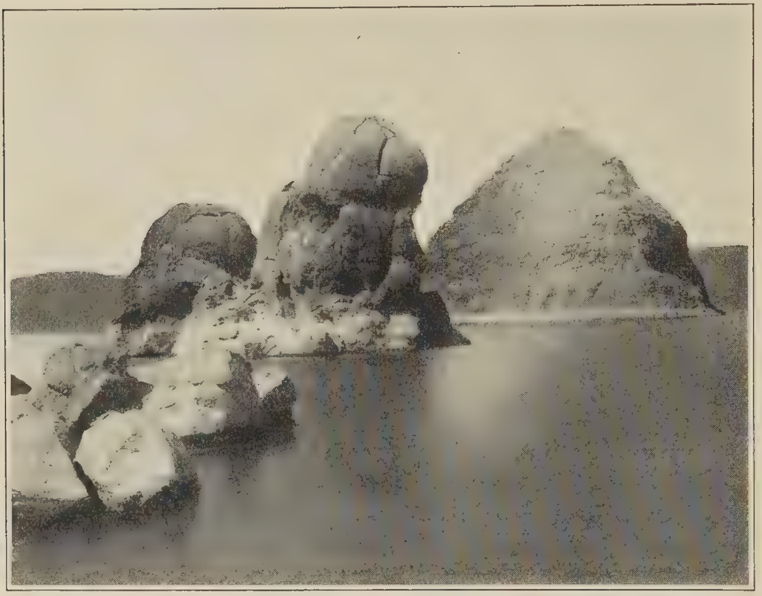

FIG. 83. Calcareous tufa in Pyramid Lake, Nevada. (Photograph by J. C. Russell. Courtesy of the United States Geological Survey)

calcium cling to the water as long as there is any water left. When normal sea water is evaporated experimentally, the sequence of deposition in saline lakes is clearly demonstrated. When 12 per cent is evaporated, iron oxide and calcium carbonate are precipitated; gypsum begins to form after 37 per cent of the water is evaporated, but common salt does not precipitate until 93 per cent of the water is gone; finally, as dryness is approached, magnesium sulphate and the chlorides of calcium, magnesium, and potash appear in the solid residue.

This normal sequence, so easily demonstrated in the laboratory, may be disturbed in nature. Lakes may go to a certain point and there hesitate to continue onward toward further concentration, or they may even become temporarily or permanently freshened. Thus their deposits may not show the orderly arrangement from the least to the most soluble salts, which would obtain if evaporation had progressed regularly to dryness.

Swamp deposits. The last stage in the destruction of a lake is accomplished when vegetation unites with inorganic sediments to convert what was formerly a clear body of water into a shallow, plant-choked waste variously described as swamp, bog, or marsh. The vegetable accumulations of this type have played an important rôle in the history of the earth as well as of man, because such deposits are the first step in the formation of coal, without which civilization could not have progressed. Plants decaying in damp, cool, swampy places form a deposit of black carbonaceous material called *peat.* The carbon gained from the air and stored in the tissues of all kinds of growing plants remains after the death and decay of the mother organisms. With the march of the seasons new plants are born, grow up, and are killed by winter frosts, to fall to the bottom of the swamp and add to the accumulation of vegetable mold. The complicated chemical decomposition which besets the dead plant material is begun through the activities of bacteria in the shoaling waters. Plants decaying under air are resolved into various gases and humous acids, which escape to the atmosphere or are carried to the ground water by rain. Little solid residue remains. Plants decaying under water, however, where oxidation is retarded, retain much of their carbon and hydrogen, which accumulates as peat. With the passage of time and as the progress of disintegration continues, peat turns from brown to black as the percentage of carbon rises. Just as lakes are converted into peat bogs by vegetation and sedimentation, so are the heads of marine bays often converted into marshes. It has been estimated that in the United States alone twelve billion tons of peat are available for fuel, a resource which has as yet been untapped because of the abundance of wood and coal. Peat, however, is cut, dried, and used extensively as fuel in many European countries.

Peat is the first stage in the formation of coal. The long history of the conversion of peat into coal is a complicated story of chemical decay, resulting in a gradual elimination of all substances in the original vegetable material except carbon and ash. Carbon is the substance which burns in coal: the more carbon, the purer the coal; the purer the coal, the better the combustion in most cases. Coals exist representing all proportions of carbon, from peat with the smallest percentage to anthracite with the highest. With the increase in the percentage of carbon, coal loses its volatile gases and, in popular phraseology, is said to become "harder." The harder the coal, the better it is as a fuel for most purposes.

In the Northern Hemisphere peaty material is now accumulating in swamps at the rate of approximately one foot in ten years. Decomposition and compression go on as this organic débris is buried under further accumulation, so that the original twelve inches of dead vegetation near the surface is reduced to one inch at a depth of eighteen feet, making the present rate of peat accumulation about one foot in a century. Coals formed from peat take varying lengths of time for their formation, depending on the percentage of carbon possessed. It has been estimated that three centuries are necessary for the accumulation of material sufficient to make one foot of good coal.

MARINE DEPOSITS

The land deposits just considered are in a sense exceptions to the general rule of nature. If sediments accumulate on land, they do so because they have successfully evaded, if only for a relatively short time, the clutches of erosion. Erosion is unceasingly struggling to degrade the land areas of the earth as far as possible. Since sea level is the line below which most agencies of erosion are shorn of tooth and claw, it is to sea level that they strive to reduce the land. Any material escaping the attack of the many instruments of surface gradation to reside for a time above the level of the sea is constantly in danger of being swept onward into the great repository of earthly waste. In the next chapter we shall consider the colossal forces of the earth's interior which have kept the tools of erosion from entirely accomplishing their purpose through all the long periods of geological time. It remains for us in this chapter to see what happens to the vast quantities of material which erosion succeeds in carrying from the land to the sea and likewise to that material which is more or less the creature of the sea itself.

The ocean basins, unlike their shallower relatives of the land, the lakes, have throughout their long history been more than able to receive all the sediment given them by the rivers and the other agencies of rock destruction and transportation, and still remain deep withal. Some of the material from the land is arranged by ocean currents, tides, and waves in interesting deposits between high and low tide. These are known as the *shore deposits*. Outward from low tide to a depth of approximately 600 feet, different types of deposits occur which are known as the *shallow-water deposits*. At or near a depth of 600 feet shallow-water types of accumulation grade into the *deep-sea deposits*. This so-called *100-fathom line* is a critical depth in the ocean, because below this depth sunlight cannot penetrate, with the result that here vegetation must practically cease to exist. At about this depth waves no longer have any power to disturb the bottom as they do in shallower water.

Very near the 100-fathom line the coarse terrigenous detritus from the land gives way to the fine muds and oozes typical of the deeper zone. We have already seen that all continents stand on submerged platforms or shelves. It was long thought that near the 100-fathom line lay the junction of the deep ocean basins and the continental shelves. More recent soundings, however, have led some able geologists to the belief that the real break in the continental plateau beyond which the declivity into the ocean depths is strongly marked lies under shallower water, in many cases being near the 40-fathom line.

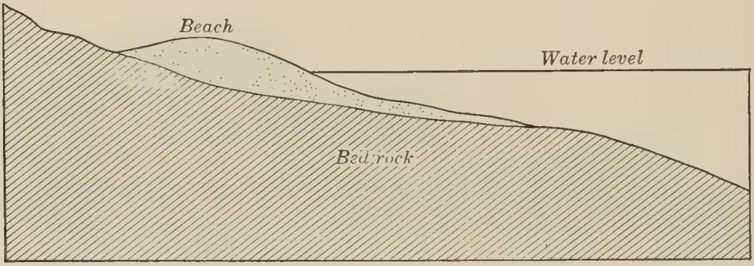

FIG. 84. Cross section of a beach

Shore deposits. It is along the seashore that most of the coarse bowlders, gravels, and sand worn from the land are first deposited. The narrow zone between high and low water is seldom wider than half a mile, but it is as long as the combined coast lines of all the world and is estimated to cover over sixty-two thousand square miles of the earth's surface. A familiar type of deposit made in this zone is the *beach*, composed of coarse materials ground up and arranged along the shore by waves (Fig. 84). Waves use a selective process in building beaches, the stronger waves throwing the larger bowlders high on the shore, leaving to the shore currents and to the lesser waves the task of arranging the finer gravels and sand lower down. Sometimes land areas that were once flooded by the sea record the fact by well-preserved extinct beaches. Materials constituting beaches are in transit. Waves and currents constantly bring particles of rock from seaward and from other shores, and the undertow is continually carrying much of the finer material away.

In some places the shore has an unusually gentle seaward inclination, and incoming waves begin to drag on the bottom and break long before the shore is reached. The line of breakers thus formed is a nucleus for sedimentation; near this line both the waves from the open ocean and the undertow from the shore drop their offerings. The result may be the development of a long, narrow island, or *barrier*, which never stands high above the level of the sea (Fig. 85).

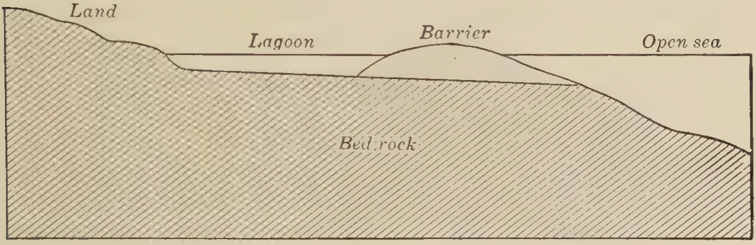

FIG. 85. Cross section of a barrier and a lagoon

Between the barrier and the shore the water is shallow and is known as a *lagoon*. Such lagoons may be filled up in time to form salt marshes.

Where a river enters the sea, sediment is likely to be deposited off its mouth in the form of a *bar*. Other bars are formed by currents, which, like prowling thieves, pick up all the loose material they can carry from shallow places, only to be forced to give up their loot where their velocity is reduced by contact with deeper water. Anything that checks the velocity of shore currents makes them deposit their burden in the form of an offshore bar. This frequently happens where shore currents encounter deeper water off the mouths of small bays. Such barricades along coasts are controlled by the configuration of the shore, the direction and strength of shore currents, and the amount of loose rock débris available for the purpose. If a current-built embankment of this type incloses or nearly incloses the section of coast line in front of which it is forming, it is a typical bar; bars projecting seaward and possessing one free end are called *spits* (Fig. 86); where strong currents wear off the end of a spit and deposit the material gained at a curving angle with the main spit, the result is a *hook*; if the end of a hook is so twisted by the currents as to join or nearly join the mainland, the deposit is called a *loop*. The tendency of shore deposition of this type is usually to render seacoasts more irregular at first and then gradually to straighten them as deposition continues. The Gulf and Atlantic coasts of North America have been greatly simplified in this manner.

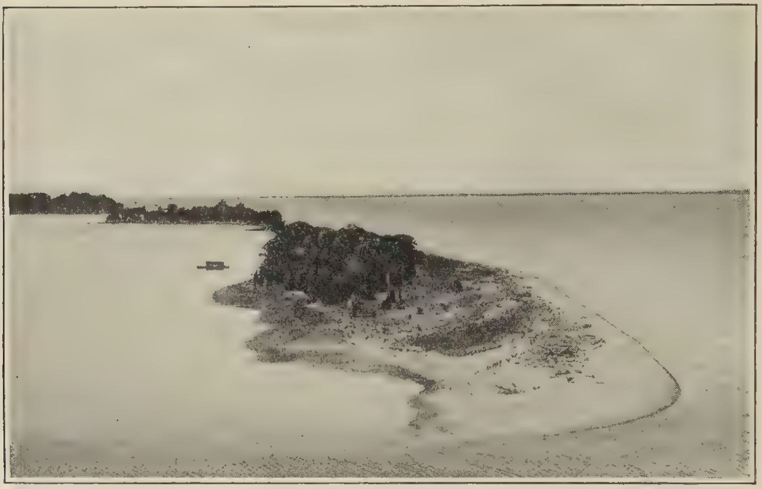

FIG. 86. A sand spit in Maryland. (Courtesy of the United States Geological Survey)

Deposits of the shore zone are sometimes beautifully and delicately marked by the tools which mold them. Ripples of water running back to the sea after being thrown on the shore by the wind-driven waves form the delicate *ripple marks* to be seen on any sandy beach (Fig. 87). Where water trickles over a sandy beach as the tide goes out, little channels are left behind known as *rill marks*. Where tidal mud flats are exposed to the baking rays of the sun, the mud shrinks and breaks up

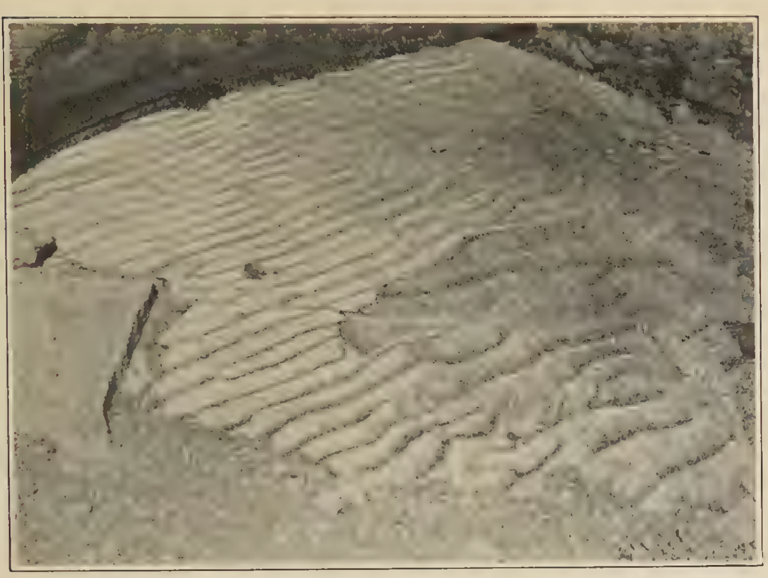

FIG. 87. Ripple marks of an ancient shore, Glacier National Park, Montana

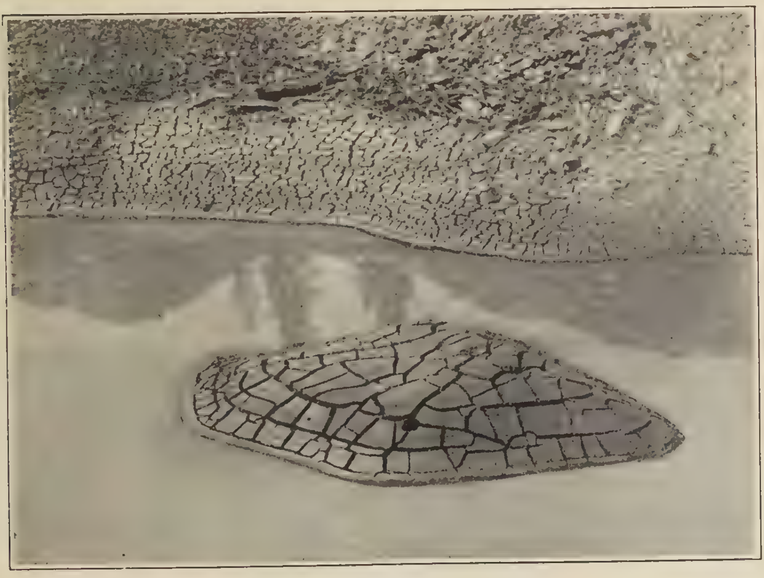

FIG. 88. Recent mud cracks

into polygonal blocks. Such cracks in the surface of a muddy shore deposit are called *mud cracks* (Figs. 88 and 89). Even the imprints of rain and hail are left on shore sediments, as are the trails and burrows of various kinds of animals that live in this belt. Such slight marks as these are often well preserved in solid rock, so that geologists can interpret them as shore deposits of ancient seas. In places as far removed from the present sea as some of the lofty peaks of the Rockies in western Montana, mud-cracked and ripple-marked rocks have been found, giving clear proof of their origin as sediment on a seashore long ages ago. The earth through its long and varied history has seen many changes in the relative position of land and water, so that it is not uncommon to find on the top of high mountains not only the inorganic evidence of formation below the sea, but in many cases the actual fossil remains of

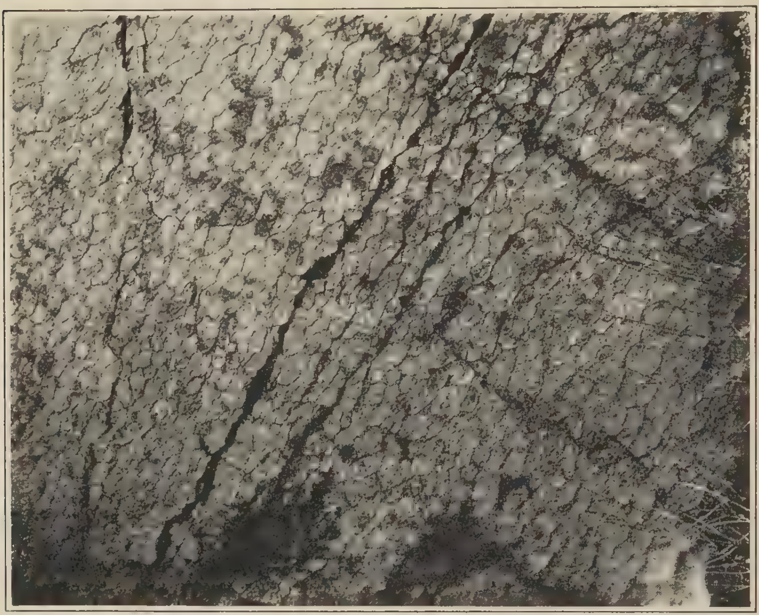

FIG. 89. Ancient mud cracks preserved as rock. (Courtesy of the United States Geological Survey)

marine creatures. The cause for these mighty reversals will be treated in a later chapter.

Shallow-water deposits. It has been estimated that ten million square miles of the earth's surface are occupied by deposits laid down between low tide and the 100-fathom line. These shallow-water deposits form the link which joins the coarse shore gravels and sands to the deep-sea muds and oozes. As would be expected, they are finer than the former and coarser than the latter, with coarse material predominating. The material here laid down is often preserved long after uplift of the land has removed the sediments far from the sea. Sometimes ancient deposits of this zone, which are among the commonest of sedimentary rocks, are of almost incredible thicknesses, to be explained in some cases only by the sinking of the shallow-water zone while débris was accumulating, thus allowing abnormally thick deposits to be built.

The zone of shallow water is the most highly populated region on earth. Here, where the sunlight gives warmth and the waves and currents keep food in circulation, myriads of sea animals and plants abound. Conditions for life on land are at best shifty and hazardous; in the shore waters of the ocean conditions are more uniform, and here, in the seas of all times and places, the fascinating pageant of organic development was enacted. Many of the creatures that lived here were buried and preserved; so after the loose sediments were raised from the sea and hardened into rock, as often happened, glimpses of the past history of life can be had. How this history has been read by the paleontologists is recounted in Chapter VII.

Deep-sea deposits. The continental shelves do not drop abruptly to the abyssal depths: the oceans grow steadily deeper beyond the 100-fathom line, but it is estimated that eighteen million square miles of the earth's surface is occupied by an intermediate zone between this line and the 1000-fathom line. Here the lower waters are not agitated by even the strongest storms and are only slightly moved by currents, whose power is feeble at such a depth. Light from the sun is almost absorbed before the bottom is reached, so that here is a zone of half light merging into the Stygian night of the abyss. Seasonal changes in temperature are barely felt, and the water near the bottom stands always at a temperature below 40° F.

Below the 1000-fathom line all is monotone. There is no light, no movement of the water. Temperatures throughout the year stand very near the freezing point. Whereas in the zone between the 100-fathom line and the 1000-fathom line fine clastic material from the land is deposited as mud, in the abyssal depths only the oozes, whose nature we shall soon consider, are found. On account of the absence of light, no vegetable life exists on the bottom, and only degenerate forms of animals are found, which feed on the organic muck dropped down from above. Many creatures, however, live in the sun-warmed surface waters of this zone, and upon death fall to the bottom, where their skeletons add to the accumulation from other sources.

Land-derived deposits. Only the finest products of land destruction are carried out beyond the 100-fathom line, and practically none beyond the 1000-fathom line. Such deposits have either a blue or a green color and are called the *blue* and the *green* muds. The former receive their color through a lack of oxidation at so great a depth; the latter are colored by a mineral which forms only in the sea. Blue muds are commoner than their associates, the green muds, and are estimated to cover seven ninths of the intermediate zone between the 100-fathom line and the 1000-fathom line.

Abyssal oozes. The best-represented material in the deep-sea oozes was derived from volcanoes as fine dust and ash. This material was carried far out to sea by the wind. After the wind tired of playing with these smallest of rock fragments, it delivered its burden to the ocean. After currents and waves had ceased to toy with the nearly microscopic bits of dust, they allowed the fine particles slowly to sink and find lodgment on the bottom. Some of this material may have been derived more directly from submarine volcanoes, which are known to exist abundantly in certain parts of the deep ocean troughs.

Mixed with these *volcanic muds* are the grains of material which had settled upon the earth from the countless meteors that are constantly entering the earth's atmosphere.

Perhaps the best-known of all deep-sea deposits are those derived from the marine organisms that live in the surface waters of all oceans. Millions of tiny creatures, some with shells of silica and some with limy skeletons, drop daily to the ocean bottoms. Lime-carbonate oozes are commoner in the shallower portions of the abyss, and siliceous oozes dominate in the deepest depressions in the sea. At great depths, where the carbonate of lime becomes scarce, the calcareous skeletons of organisms are replaced by a *red clay*, which was formerly thought to be largely organic in origin, but is now believed to result from the decay of inorganic material.

Much material of less certain nature is produced by chemical decay of volcanic, cosmic, and organic substances on the sea bottom. The net result is the production of muds that have no counterpart anywhere else on earth. Since deep-sea deposits have never been conclusively proved to exist among the many diverse sedimentary formations known on the continents, it is believed that although the edges of the sea may advance on and withdraw from the low areas of continental masses, the great depths of the sea have always been deep, and at no time in geological history were they elevated and converted into land.

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CHAPTER IV

SUBTERRANEAN PROCESSES OF DEFORMATION

Deeply emboweled in the earth's interior lies a restless energy which shows itself at the surface in movements of the lithosphere. All kinds of movements are constantly racking the globe, from tiny rapid ones to gigantic slow ones. These movements, which may be horizontal, upward, or downward in direction, are referred to collectively as *diastrophism.* The result of diastrophism is the distortion of the lithosphere and in consequence a disturbance of the orderly cycles of surface erosion, sketched in the preceding chapters. It is believed that the earth is a cooling body, and that in cooling it contracts so that the surface puckers and wrinkles to fit the decreasing volume of the inner core, much as a potato drying in the cellar during the winter loses moisture, shrinks, and wrinkles. Although no adequate explanation is yet known for all the subterranean processes, there is valid evidence for the shrinking of the earth as a basic fact with which we can at least start an explanation of the movements observed and recorded in the rocks. In the present chapter this evidence will be considered.

If we assume for the moment that the globe does shrink, it is evident that the resultant of all past and present diastrophic movements was and is downward toward the center of the earth. The movements of the surface shell, however, are of the nature of wrinkling and may be downward in some places and upward or horizontal in others.

Closely related to diastrophism are other processes, known collectively as *vulcanism,* whereby great masses of fluid rock are moved outward toward the earth's surface. The former type of movement is widely known in the phenomenon of earthquakes; the latter is typified by volcanoes. Since the important volcanic belts of the earth are located along great rifts where differential movements in the lithosphere have taken place, it is believed that in these belts of weakness the rock of the interior has in some way been forced upward. We shall now consider the more significant manifestations of diastrophism and vulcanism and see how far man's ingenuity has been able to account for the causes.

DIASTROPHISM

Elevation of land. The sea level is the datum plane by which the extent of earth movements is measured. Since the oceanic segments of the lithosphere are as unstable as the continental masses, movements of land along seacoasts show merely the relative deformation. In many instances it is difficult to determine whether the ocean basins have sunk or the continents have risen. It must be remembered that although a seacoast may be observed to rise or sink with reference to the ocean level, it is not unlikely that both land and ocean basins are sinking, the latter at a greater rate. This, of course, is due to the contraction of the earth as a whole.

Plenty of recent evidence of the change in level of lands bordering the ocean is preserved in human records. A famous example of such evidence is the history of the Roman temple of Serapis, built on the shore of the Mediterranean at Pozzuoli, near Naples. The three marble columns still standing are perforated by the borings of marine mollusks, and give clear proof that the temple had sunk nearly twenty feet into the sea and afterwards was reëlevated. Some documentary evidence is extant which substantiates the evidence of the boring sea animals, whose shells are even yet to be seen in the columns now high above water. Tide gauges which have been tended for a long period of time in Sweden show that the Scandinavian Peninsula has been slowly rising for a long time.

Such movements are known to have taken place in the more remote geological past in regions where wave-cut cliffs and terraces have been elevated far above the sea which produced their characteristic forms. Raised beaches likewise give token of the rise of seashores. The presence of ancient shore deposits and the fossil remains of organisms far from the present sea tell of changes in level long since consummated. Fossil sea shells preserved in the rocks of high mountain peaks several thousands of feet above the present sea level speak eloquently of the changes which the earth has seen.

The sinking of land. Evidence of the subsidence of seacoasts is not less striking in some places than that of elevation in others. Such estuaries as Chesapeake Bay are broad river valleys drowned by the down-warping of the coast. Where rivers build great deltas which heavily weigh down small sections of the earth's crust, these areas are apt to give way and sink under the stress, as is shown by borings in the delta of the Mississippi. Submerged forests and peat bogs are found in many places. Along the north coast of Egypt ancient tombs once high on the seashore can now be seen sunken below the blue waters of the Mediterranean.

Such movements are not the peculiar habit of seacoasts, but are merely best observed in the proximity of the sea. It is believed that diastrophic change has been felt and is being felt on all lands and under all oceans; that these movements are the inescapable result of a cooling earth. Through evidence similar to that just cited it is known that the east coast of Greenland is slowly rising and that the west coast is sinking; that almost the entire Pacific coasts of North and South America are rising and that the southeastern coast of China is sinking. Other regions of present movement could be mentioned, and the many movements, both local and of great extent, which affected blocks of the earth's crust during its long history would alone form material for a large treatise.

Types of earth movement. Delicate instruments for the detection of earth movements have been devised by man to record tremors which could not be recognized in any other way. These seismographs, as they are called, show that the old earth, like an old man, is constantly trembling. All evidence points to the fact that some parts of the earth's crust are rising while others are sinking; still others appear motionless. Some movements are local and rapid and are known as earthquakes; others are of continental proportions and appear to be ponderously slow. In the history of the earth two important types of diastrophism can be distinguished: (1) that which produces upward, downward, or tilting movement in blocks of great size, and is known as *epeirogeny*, or continent-forming movements; (2) that which produces wrinkling and fracturing along belts of weakness in the earth's crust, and is known as *orogeny*, or mountain-building movements.

The distinction between the slow and the rapid type of earth movement is perhaps too finely drawn in the minds of most geologists. Continent-forming and mountain-building movements are probably the result of a large number of rapid movements continued through a long period of time. Because of the ponderous size of the result, the rapidity of the many movements producing it is apt to be overlooked. It is not unlikely that all movements which harass the crust of the earth proceed with jerks similar to those which produce earthquakes.

Earthquakes. When the earth suffers a short, sharp, rapid readjustment along moving blocks in its crust, the terrifying phenomenon of an earthquake may be felt on the surface. In a geological sense earthquakes are minor spasms of movement and are of slight importance compared with the great continent-forming and mountain-building movements. Earthquakes, however, throw light on the forces which are struggling for an outlet in the earth's interior, and since they have had great influence on the activities of man, they have been studied out of proportion to their importance as instruments of geological change.

Earthquakes are produced by sudden shock in the earth's interior, which sets up a train of waves that vibrate through the outer crust. The most common cause of such a shock is the fracturing of rock and the slipping of one block along another. The seismograph has thrown light on the nature of earthquake vibrations. It is now known that at least three distinct sets of vibrations are started by an earthquake, one set traveling round the earth, and the other two sets through it. Of the two sets, that which travels faster moves at the rate of about three hundred and seventy-five miles a minute along a curved line approximating the chord from the point of origin to the point of observation. The surface waves are of variable velocity, depending on the nature of the rock through which they pass, but they never acquire the great speed of the waves moving through the earth's interior. The seismograph announces the beginning of an earthquake tremor by recording the two sets of preliminary vibrations which result from the waves that pass through the earth's body. Then follows the recording of the strong tremblings of the main shock, produced by the surface waves. A series of slight vibrations is recorded at the end of the shock. Contrary to what might be expected, the amplitude of earthquake vibrations is usually very small. The destructive power of the vibration lies in its suddenness and not in the distance through which rocks move in the shaking. An earthquake whose amplitude is but a quarter of an inch can destroy a chimney; one whose amplitude is three quarters of an inch can ruin an entire city. The path traveled by a single particle of rock during an earthquake may be very complicated, as shown in Fig. 90.

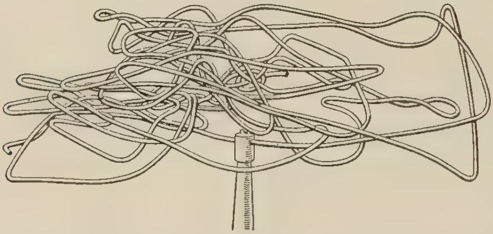

FIG. 90. Wire model showing the movement of a particle of earth during an earthquake. (After Sekiya)

Cracks in the earth's outer shell which have been produced by shock and along which movement has taken place are called *faults*. The great earthquake which destroyed San Francisco in 1906 was the result of movement along such a fracture, known as the San Andreas fault. This fault has been followed for nearly five hundred miles along the California coast. Although movements on faults are most commonly vertical, the dislocation which produced the San Francisco disaster was horizontal. By fences which were broken and moved apart along the rift, it is known that the displacement amounted to as much as twenty feet, and that movement occurred over at least half the length of the fault. Great fissures open along the line of such active fault planes, and when the movement is vertical *fault scarps* are produced (Fig. 93). Impressive escarpments, sometimes as much as five thousand feet high, have been produced by dislocation of blocks in the earth's crust. These and other peculiarities of the structure of the lithosphere will be treated in Chapter V.

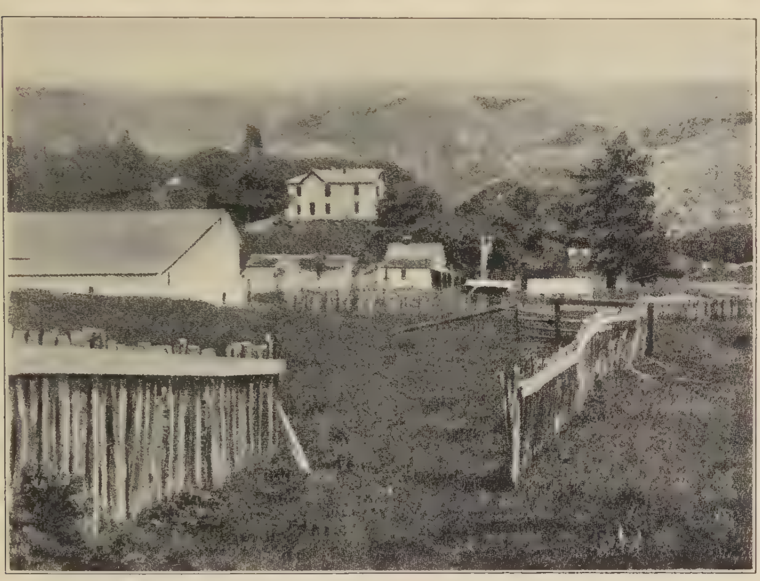

FIG. 91. Fence parted by horizontal movement during the California earthquake of 1906. (Photograph by G. K. Gilbert. Courtesy of the United States Geological Survey)

Earthquakes are not an infrequent phenomenon, many thousand occurring annually. Fortunately most of these are perceptible only by the delicate mechanism of the seismograph. Others, however, are highly destructive to life and property. In general, earthquakes are most frequent where geological change is taking place, — for instance, near volcanoes, new mountain ranges, rising coast lines, and in the places where rivers have built large deltas that weigh down and weaken the crust beneath. One great seismic belt where earthquakes are frequent engirdles the Pacific Ocean, circling round the Pacific coasts of South and North America, through the Aleutian Islands off Alaska, along the island festoons which border the eastern coast of Asia. The other great belt circles the earth through the Mediterranean, across the bed of the Atlantic Ocean to the West Indies and Central America, thence to Hawaii and Japan, China, and northern India back to the Mediterranean in Asia Minor. These belts never diverge far from coast lines where the land is rising and the ocean basins sinking. Sometimes submarine earthquakes take place along the oceanic portions of seismic belts and are often followed by great sea waves which inundate and spread disaster along low coasts. In 1896 such a wave took the lives of twenty-seven

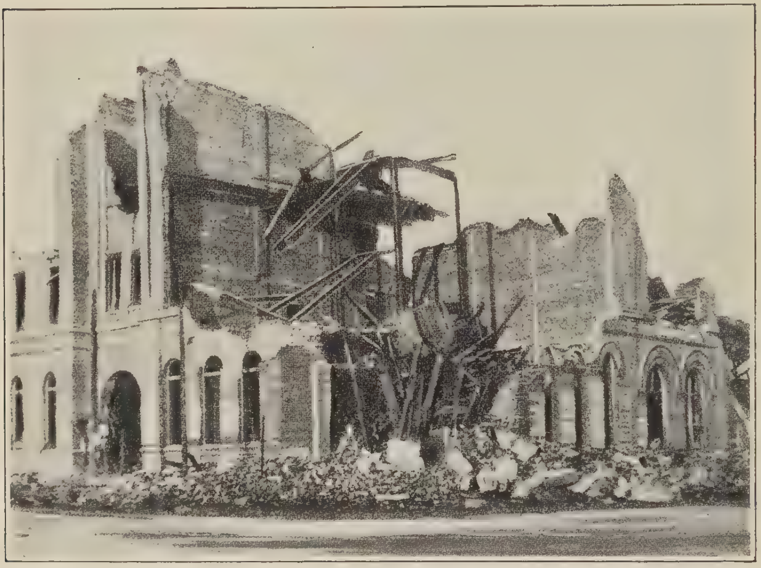

FIG. 92. Building in San Francisco wrecked by the earthquake of 1906. (Courtesy of the United States Geological Survey)

thousand people in Japan. Sea waves of this type are not uncommon along the shores of lands bordering the Pacific Ocean.

Continent-forming movements. The rapid trembling of a section of the earth's crust during an earthquake, causing vibrations to be sent through such relatively weak surface structures as houses, can produce untold damage. Rocks, however, are made of stronger material and are little affected by earthquakes. Apart from an occasional fissure, a fault escarpment, a landslide, or the disturbance of ground-water conditions locally, earthquakes do little to distort the earth's surface. Spectacular and terrifying as they are, individual earthquakes are relatively unimportant in molding the destiny of the earth itself. Contrasted with the agitated trembling of the earthquakes are the slow warping movements of continents, which perhaps are the result of many earthquakes, but in the aggregate appear to be slow and massive. These movements have been of the utmost importance in the history of continents, because through them the sea has periodically been allowed to infringe upon the land, bringing with it deposition and the

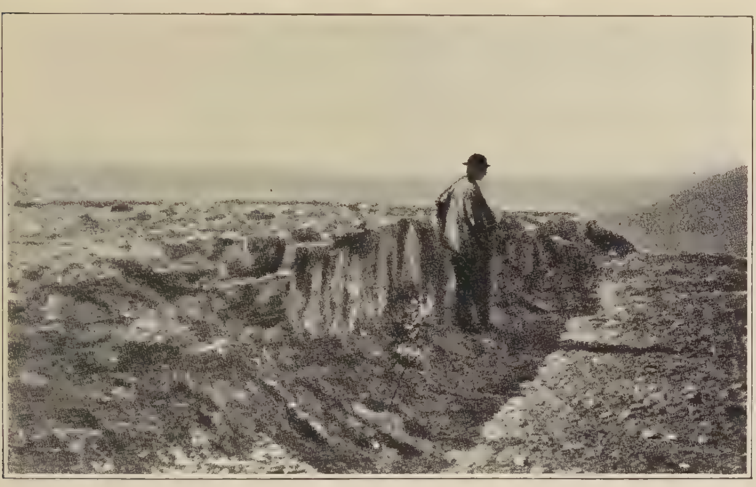

FIG. 93. Fault scarp formed during a recent earthquake in Alaska. (Courtesy of the United States Geological Survey)

migration of marine creatures over new territory. Later, when the sea is expelled, its deposits are left behind to record its former presence. By such gentle land movements climates are affected, with the attendant change in the lives of living creatures. We have seen how erosive agencies tend to wear land to sea level. Unless the land is renewed by uplift, all continents must be swallowed up by the sea. Geological history shows that again and again the land has been uplifted by gentle epeirogenic movements, thus thwarting the designs of erosive destruction and preserving the continental masses.

These continent-building and continent-renewing movements started to take place very early in the history of the earth. As far back as the records can be read, the major relief features of the globe, continents and ocean basins, existed. There seems to be no evidence for the formerly widespread belief that with the passage of time deep ocean troughs were raised into land, while great land masses foundered into the abyssal depths. The original configuration of the earth's surface seems to have been preserved with more or less fidelity. It is true that arms of the sea have often entered the land and deposited sediments, but in every case of this sort the invading seas were shallow and transitory and in no way comparable to the deep ocean basins. Of this the sedimentary rocks and their entombed fossil plants and animals give ample proof. It is true that in some places the outline of continents has changed by the foundering of rock along coasts, and in other places by the building seaward of the products of erosion. Land connections between the several continents have likewise suffered repeated change, resulting in the periodic isolation and rejoining of neighboring continents. On the whole, however, that fundamental property which in the beginning caused continents to stand high and ocean basins to lie low has exerted a dominant control throughout the long history of the globe. This property may be the result of a difference in densities between the rocks of the land masses and those underlying the ocean, the former being somewhat lighter than the latter. In the dim formative stages of the earth, long before it was inhabitable by living things, there seems to have taken place a primary segregation of materials, the heavier rocks underlying the depressions, and the lighter rocks forming the protuberances on the earth's surface. All subsequent movements of a continent-building nature have worked on this original separation as a basis, so that the grand result of oft-repeated movements was to preserve the lighter rocks in the continents as positively rising segments, while those under the ocean basins remained depressed. It is true that while great continental blocks like the high plateau of Tibet have risen, other continental blocks like that under Death Valley in California have sunk. Epeirogenic movements may up-warp parts of a continental mass and down-warp others; they may lift wide plateaus vertically and allow other areas to sink along great rifts. Nevertheless the total effect of continent-forming movements on all continents throughout all their existence has been to preserve their elevated position on the surface of the globe.

Mountain-building movements. Mountains are the most conspicuous features on the face of the earth. While no theory to account for the origin of mountains is thoroughly satisfactory, it is necessary in any explanation to assume as a basic postulate that the earth is a cooling body with a hot rigid core and a cold crust. With the loss of heat in the interior, shrinking would ensue, with the result that great areas of the outer crust would wrinkle and fold as the excess surface area accommodated itself to the shrinking interior. The earth's crust would naturally give way and buckle in the areas where the rocks are weakest. When mountain ranges are examined, it is seen that they nearly always form in regions of great sedimentary accumulation — belts which had been weak, perhaps, from the beginning and which had sunk and allowed the sea to enter and lay down its burden of sediment. Such troughs, which formed narrow and shallow seaways on land for invading ocean waters, are known to have existed on all continents during most of geological time. Weakness breeds weakness in such troughs, since their original tendency to subside is augmented by repeated invasion and deposition by the sea. When the time comes for the earth to yield to the stresses set up in its outer shell by the shrinkage of the inner core, the thick sediments in such troughs are easy areas of relief, and here intense buckling and lateral thrusting take place. Most mountain ranges of the earth stand as records of such yielding in relatively narrow belts of weakness. It can be seen that mountain-building, or orogenic, movements are the principal method whereby the earth fits its surplus of skin over its shrinking skeleton. In some mountain ranges the folded sedimentary rocks show a shortening of over one hundred miles, and ten to fifty miles is not uncommon.

Causes of diastrophism. In looking for an explanation of diastrophism in the literature of earth science the student is amazed at the great bulk of theory to match a modicum of fact. The interior of the earth is inaccessible to the searching eye of the geologist and is known only inferentially from a study of surface phenomena. For a long time geologists had accepted the ideas of the great French mathematician Laplace as to the origin of the earth. According to Laplace the earth was formed from a gaseo-liquid ring thrown off from the ancestral sun. This ring collapsed and cooled to form an earth with a thin hard crust of solidification around a hot liquid interior. It is now known through several lines of evidence that the earth probably is, and certainly acts like, a solid, or at least a highly rigid body which cannot be wholly liquid within. Foremost among the lines of evidence invoked to prove the solidity of the earth are earthquake waves, whose speed and nature of transmission imply a solid or highly rigid medium. Since the proof of the horizontal contraction of the earth's surface is present in every folded mountain range, we must accept it as a fact. Only one possible deduction is left: when the surface of a solid sphere contracts, it does so only as the result of the diminishing volume of the sphere as a whole.

Professor Chamberlin of the University of Chicago, who is perhaps the foremost American investigator of diastrophic principles, points out that the volume of the earth depends upon two sets of opposed forces. Gravity is probably the most important of the forces tending to concentrate the materials of which the earth is constructed. This great force acts upon all substances to pull them toward the center of the globe. As minor assistants to the force of gravity there are (1) *cohesion,* the power of small particles of matter to attract and stick to neighboring particles; (2) *chemical combinations* which make for greater density of materials under pressure; and (3) *subatomic energy,* the extent of which is not known, but which in part at least may produce condensation. In resistance to these forces are those which antagonize and tend to prevent condensation, foremost of which is heat. Substances expand when heated and contract when heat is lost. To the force of heat are allied certain molecular and nonmolecular forces that combat condensation. While it is not possible here to discuss all the resultant and attendant reactions which follow the struggle between these two giant contenders with their coterie of assistants, it is sufficient to say that if one did not weaken, the impossible situation of an irresistible force meeting an immovable object would be realized.

The forces of heat seem to give way to the forces of gravity, and the earth, since it is essentially solid, contracts as a whole. Unfortunately, loss of heat alone does not explain the mechanics of earth movements. If these movements, particularly the intense mountain-building variety, took place regularly, loss of heat alone might suffice as an explanation, but it is known that such movements are periodic and some believe rhythmical in their occurrence. There is only one conclusion possible in regard to the periodicity of great diastrophic movements: that since these movements seem to involve a large part if not the whole body of the earth, the earth must be highly rigid as a whole, because the outer shell is known to be weak and incapable of storing great stresses. Geology has progressed far in its search for the causes of diastrophism, but it is faced by the still unexplainable paradox, an earth whose outer crust is weak and constantly yielding to stress by warping and fracturing, and whose inner core is constantly accumulating stress to yield only periodically to relief by movement.

VULCANISM

We have seen that in losing heat the earth contracts and is deformed. In a study of living volcanoes we see one of the important means of escape for the internal heat. Vulcanism has been displayed on a far greater scale in the past than at present, and regions which were once the sites of vigorous volcanic activity are now peacefully quiet. Vulcanism, however, is not dead. At least in certain belts where vulcanism is common today, the earth gives evidence of great interior heat yet to be dissipated.

Vulcanism is the natural result of the earth's shrinkage. As internal heat passes away, gravity pulls more strongly upon the heavier rocks of the earth's framework, so that the lighter constituents are pushed outward to make room for the centerward settling of the heavier. In this readjustment many factors combine to render the lighter materials fluid, so that they can more easily move from places of greater to places of lesser stress. The nature of these factors is not completely understood, as we shall see later.

Fluid rocks forced outward toward the surface of the earth may lose so much heat in the process that they congeal before the surface is reached; in many places such rock bodies are exposed where erosion has removed the rock above. They are known as *intrusions*, that is, igneous rocks which intrude themselves in the outer crust of the earth from the deeper interior. More successful rocks of this type reach the surface and are called *extrusions*. The latter give rise to the eruptive phenomena which are popularly termed volcanic, although they represent only the surface manifestations of the great ascensive action of fluid rock working outward from the earth's interior.

Intrusions. The nature of the environment under which intrusive rocks form makes them distinct in appearance and of different texture and shape from their close of kin, the extrusive rocks. Both types belong to the great rock group whose origin is in a liquid mass, or *magma*, deep within the interior of the earth. In both types the magma freezes when sufficient heat is lost, so that solid rock of various kinds is born. These kinds will be treated more fully in the following chapter. Since the intrusive rocks are deep-seated and congeal before reaching the surface, their heat is lost gradually. This allows the individual minerals in the parent melt to grow, with the result that intrusive rocks are more coarsely crystalline in texture than other igneous rocks which have cooled more quickly. Since intrusive rocks are under pressure of confining walls, the gases which form part of all magmas are not allowed to expand rapidly, but are forced out gradually so that the resulting rock is compact and not riddled with gas cavities. Thus the pedigree of intrusives controls the nature of the ensuing rocks: they are distinguished by their compact, crystalline texture. As intruders among the formations whose positions in the crust of the earth had long been established, the intrusives take a characteristic stamp from their manner and place of birth, as we shall see.

Dikes. Where fluid rock is forced into a crack or fissure, solidification produces a *dike.* Dikes are more or less steeply inclined, are often vertical, and are usually to be told from the surrounding *country rock* by differences in color, texture, and composition. The igneous tide rising from below has forced its way into untold thousands of fissures in the weak outer crust of the globe, and in many places the results are conspicuously displayed where erosion has removed the overlying material. Dikes normally fill cracks which develop across the bedding of sedimentary rocks, and as a result they are always steeply inclined. In some places, however, they fill the cracks in other igneous rocks which had risen and congealed at an earlier date. Dikes are of all sizes, from insignificant leaves less than an inch thick to great tabular masses several hundred feet across. In some places they have been traced many miles on the surface. Dike rock may be harder or softer than the country rock; in the former case, after erosion has uncovered the intrusion, the dike may stand above the general surface like a wall, and in the latter case it may be

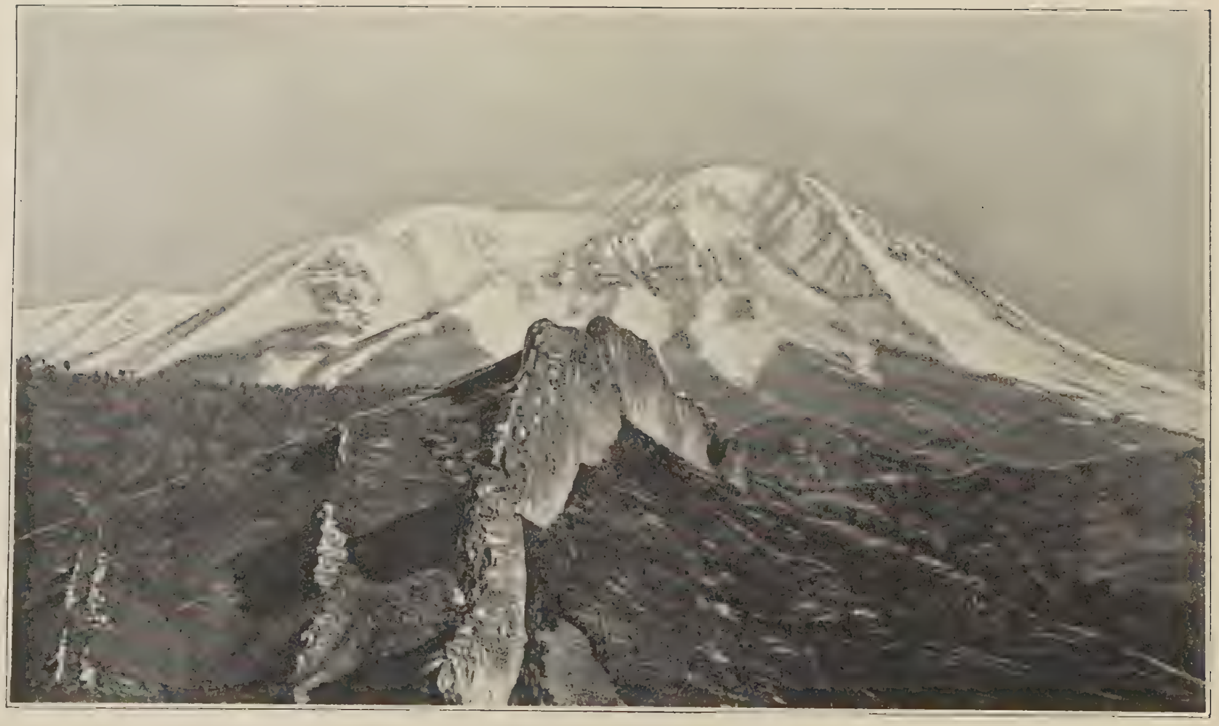

FIG. 94. Dikes in Colorado bared by erosion. (Photograph by G. W. Stose. Courtesy of the United States Geological Survey)

marked by a hollow. In places dikes of different ages may cut each other as well as the country rock, forming a tangle of rock structures with a complicated history.

Sills. It often happens in the outward crowding of liquid rock, where bedded sedimentary rock is encountered, that the fluid magma insinuates itself between the bedding planes of the country rock and creeps for many miles before freezing. Thus horizontal or slightly inclined masses of igneous rock are formed whose thickness is small and whose breadth is great. Such *sills* may run for miles between two beds, but generally they cut across to another bedding plane where they may continue to move along conformably. Sills, like dikes, are of all sizes. The famous Palisades of the Hudson are formed from a sill of unusual extent, more than eight hundred feet thick in places.

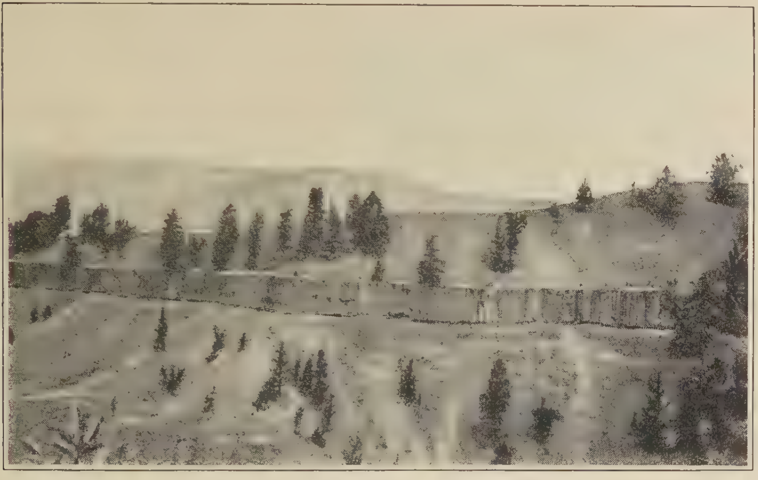

FIG. 95. A sill in Yellowstone National Park

Laccoliths. Mushroom-shaped masses of magma squeezed in between the bedding planes of sedimentary rocks, flat below and arched above, are called *laccoliths.* These are the corpulent big brothers of sills, differing from sills only in size and shape. When laccoliths form they distend the overlying sedimentary formations, so that tension cracks are often produced which are filled with dikes from magma given off by the intruding laccolith. Laccoliths probably represent the last stages of an intrusive magma grown so stiff by cooling that it could more easily upbow the confining strata than force its way forward between the bedding planes. Like dikes and sills, laccoliths vary in size and shape. They may be a mile thick and several miles in diameter, as is shown in the Henry Mountains of southern Utah, which are composed of a group of laccoliths denuded and dissected by erosion.

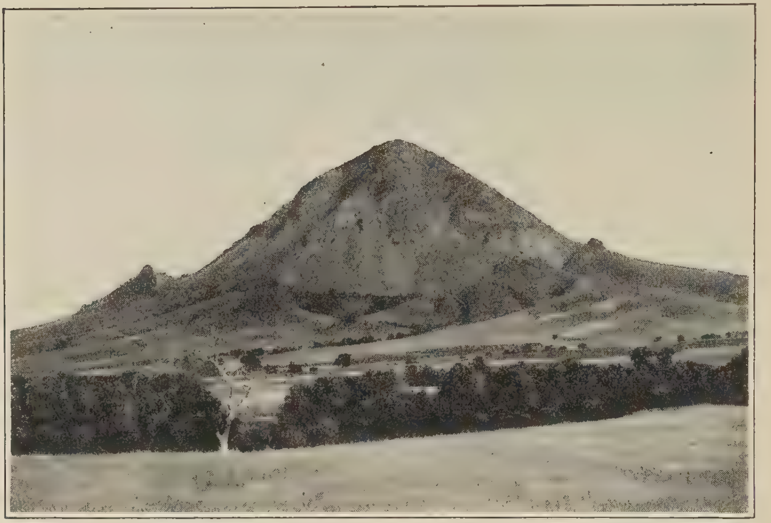

FIG. 96. A laccolith in South Dakota partly uncovered by erosion. (Photograph by N. H. Darton. Courtesy of the United States Geological Survey)

Notice the upturned edges of sedimentary beds at the base

Batholiths. The greatest of all the intruded igneous rock bodies are those large masses whose roots are deeply buried in the earth's crust, known as *batholiths,* which means "deep stones." While erosion has uncovered many batholiths and has shown them to be of great areal extent, in some cases hundreds of square miles, the bottom of a batholith has never been revealed. Unlike the other intrusives, batholiths enlarge downward and are lost deep in the earth's crust. Small batholiths a few hundred yards to a few square miles in surface extent are called *bosses* or *stocks*. These are usually irregularly circular in ground plan; the larger batholiths are of diverse shapes. In other particulars, including downward enlargement, the two are similar. Stocks and batholiths are upwellings from reservoirs well below the surface of the earth; in covering thousands of square miles they have been effective means of counteracting the destruction wrought by erosion. The mechanics of the intrusion of such great masses of liquid magma into the upper crust is not as yet well understood. Does the magma rise by pushing, uplifting, and shattering the impeding country rock, or does it melt and dissolve the rock, literally chewing and eating its way to the surface? It is probable that in the lower parts of the crust, where openings do not exist, the invading magmas rise only by virtue of their power to assimilate the material in their path, and that on entering the upper zone of weakness the stiffening magma works into cracks and fissures, partly rupturing and partly breaking and digesting chunks from the roof rocks above.

Extrusions. Where rising magmas succeed in breaking out on the surface of the earth before all their heat is dissipated, the result is the most awe-inspiring of all geological phenomena. We have seen how liquid rock, by congealing before the surface is gained, forms solid rock which is characteristically close-grained and crystalline. The history of intrusives is a slow struggle for relief from the Titanic forces which urge them outward and a slow death as their heat and energy are dissipated and shattered in the attempt. Those magmas which reach the surface are suddenly freed from the great pressure that confined them in their subterranean prisons and from the insistent forces that battered them against the confining walls. The result of such freedom is often spectacular. Gases in the liquid rock may explode with great violence, hurling the rapidly cooling magma in all directions. That part of the melt which is not blown to fragments flows over the surface as lava, carrying destruction to all living creatures in its path. As with the intrusive rocks, their method of birth puts its stamp on extrusive rocks. Freed from subterranean restraint, magmas extruded on the surface are not uncommonly blown up by their gases, so that the resulting rocks are characteristically full of cavities made by countless bubbles of expanding gas. Again, contact with the air dissipates their heat, with the result that cooling takes place so rapidly in extrusives that crystals have no time to grow. The resulting rocks are glassy or slaggy, and if individual crystals develop at all, they are tiny and inconspicuous in an indistinct ground mass of many fused minerals. Thus it happens that from the same parent magma may come these two unlike offspring: the compact, well-crystallized intrusive rock and the gas-ridden, amorphous or very poorly crystallized extrusive rock.

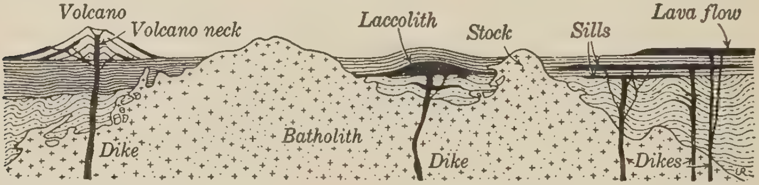

FIG. 97. Diagram to illustrate the occurrence of igneous rocks. (Modified after Pirsson)

Volcanoes. Openings in the crust of the earth through which liquid rock is allowed to issue from the interior are generally known as volcanoes. The typical volcano consists of a vent, or crater, in a steep-sided, cone-shaped hill or mountain, out of which from time to time come liquid rock and what appears to be smoke and ashes, but is really dust-laden steam. The cone through which volcanoes emit their infernal substances is always the result of the solidification of lava flowing away from and falling around the vent, and never the cause of the volcano. It is natural, therefore, that since the presence of cones is to some degree fortuitous, they vary from small cones only a few hundred feet high to great mountains standing thousands of feet above their bases. The most impressive volcanic peaks in the world are those which form the Hawaiian Islands. These were once submarine volcanoes which built their cones on the floor of the Pacific Ocean in water over three miles deep. They reared their heads upward and, not content with reaching the surface of the sea, continued to grow until a few of them now stand nearly fourteen thousand feet above sea level, making their total height from base to apex over five miles. In all nature there is nothing to excel the grandeur of the great volcanic peaks of the western part of North America — Mt. Hood, Mt. Rainier, Mt. Adams, Mt. Shasta, and Mt. Baker, all near the main range of the Cascades, but each set apart in dignified isolation, with eternal snow on their summits, which rise from ten thousand to more than fourteen thousand feet above the sea.

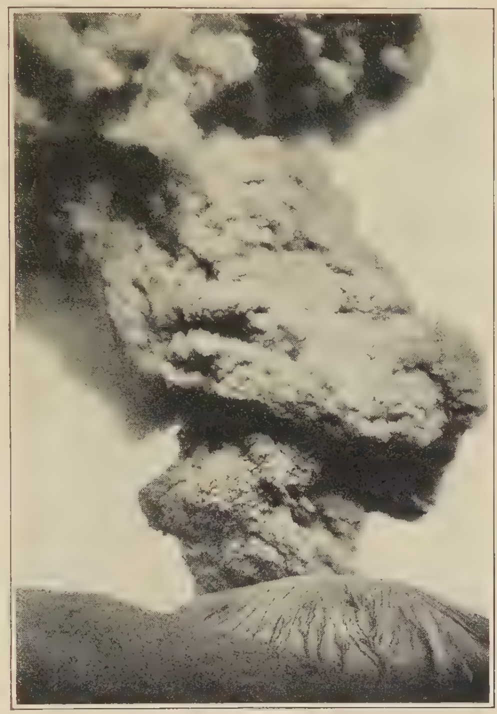

FIG. 98. Vesuvius in eruption

There is much individuality and personality in volcanoes. Some may pretend death like the opossum, only to break forth in vicious eruption after a long quiescence. Thus Vesuvius was thought extinct at the time of Christ, but it exploded A. D. 79, blew off half its cone, and buried the city of Pompeii under a rain of ash and a deluge of lava. Since that time it has subsided into a state of intermittent activity, always steaming and throwing up rock, so that close approach to its crater is dangerous. On the other hand, Kilauea in the Hawaiian

Islands, which has had the longest-known record of sustained activity, is also the most gentle volcano on earth. The classification of volcanoes into dormant, active, and extinct is arbitrarily arranged by man, who measures time in terms of his own short span of years. "Extinct" volcanoes may suddenly burst into new life, whereas those known to have erupted within historic times and called "dormant" may never erupt again. With the exception of volcanoes in eruption, which can correctly enough be termed "active," there is no way to presage future events. Mt. Rainier, placid enough now under its blanket of snow and moving ice, but still slightly steaming, may sometime burst into renewed life.

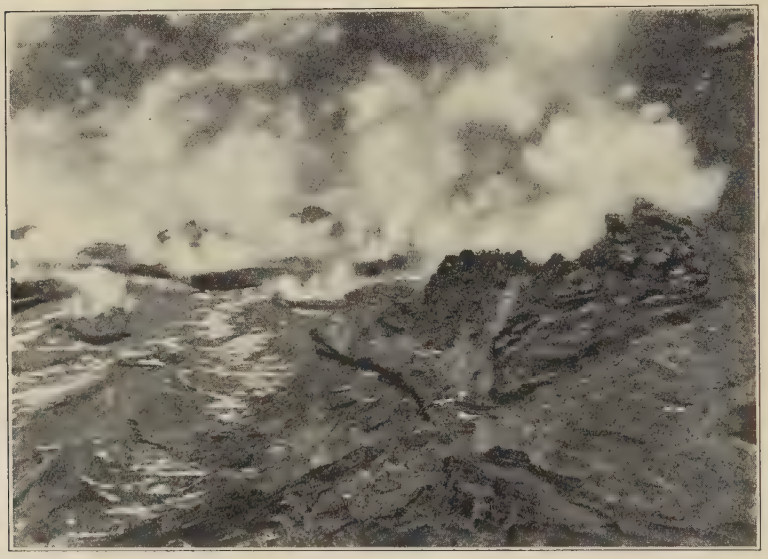

FIG. 99. Halemaumau, the "fiery pit" of Kilauea, an active volcano of the quiet type. (Courtesy of Dr. R. T. Chamberlin)

The behavior of active volcanoes is of two distinct kinds: the *explosive* type, exemplified by Vesuvius, and the *quiet* variety, represented by Kilauea. In the former, eruption occurs suddenly and without warning; great clouds of smoke are violently thrown into the atmosphere to the accompaniment of stentorian booming from within the cone. After the initial paroxysm, which hurls thousands of tons of ash and dust high into the air, a deadly flow of lava is apt to follow, and then quiet — for a time. Such is the nature of Vesuvius; of Krakatoa in the Dutch East Indies, which suddenly in 1883 blew its head off with such explosive violence that the detonation was heard two thousand miles away and the shock produced great waves which swept over hundreds of island settlements and killed tens of thousands of people; of Katmai on the Alaska Peninsula, whose dust from the eruption in 1912 obscured the light of the sun for over two days, plunging the surrounding country over a radius of one hundred miles into complete darkness; of Mont Pelée in the French West Indies; of Bandai-san in Japan; and of many other volcanoes whose eruptions have been of historic importance. The quiet type of volcano is marked by gentle exudation of lava without explosion and the projection of rocky material into the air. The best examples of quiet volcanoes are to be seen on the island of Hawaii, which has Kea and Hualalai, now apparently extinct, and the famous active volcano of Kilauea. A laboratory for the study of Kilauea is located close to the crater.

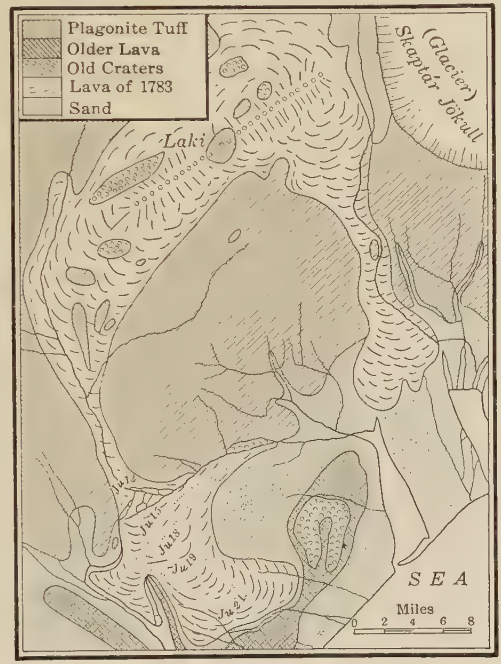

FIG. 100. Map showing the extent of a fissure flow in Iceland in June, 1783. (After Helland)

Fissure eruptions. Extrusion from centralized volcanic vents of the explosive and quiet types is in vogue in the modern world, but was not always so in the remote past history of the earth. In several countries great flows of lava forming level plains many thousands of square miles in extent, too large to have issued from single volcanic openings, have been built up.

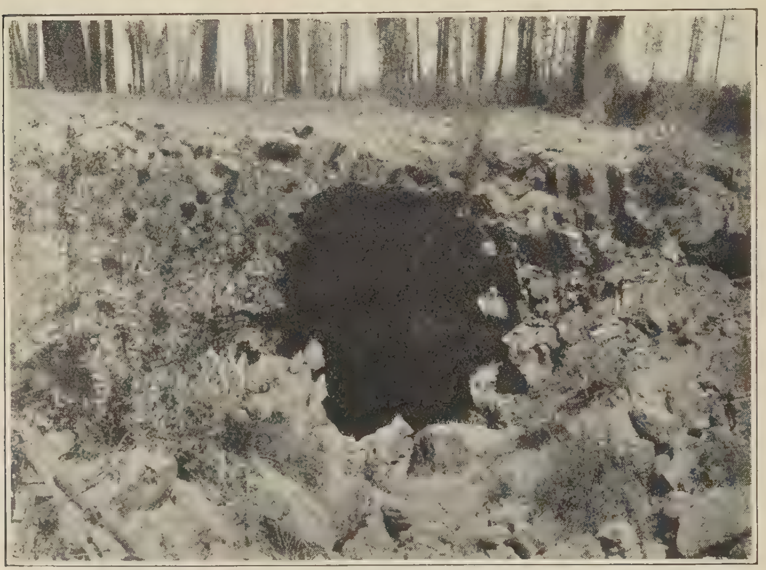

FIG. 101. A lava tunnel in a fissure flow in Oregon

When lava hardens a crust forms first over the outside. The liquid rock within may still flow, usually along definite channels. At times the lava flows out of such a channel, leaving a cave or tunnel in the resulting rock

Such lava plains are in some cases thousands of feet thick, and because of their gigantic proportions and the absence of any cones from which they might have welled, they are thought to have issued from fissures in the earth's crust. Lavas of this type must have been very fluid to spread so far before congealing.

Recent eruptions from fissures in Iceland, where successive lava streams have built up a mass one hundred feet deep and over two hundred square miles in extent, give some idea of the origin of the great ancient lava plateaus. The grandeur of past flows, however, is scarcely realized in a study of the relatively insignificant modern ones. At a time not so remote as geological time is reckoned, over two hundred thousand square miles of what is now Washington, Oregon, Idaho, and California was buried under lava which accumulated in places to a depth of three thousand feet. Mountains were buried. That the lava did not come in a single flow is shown by the layers of soil between successive outpourings, clearly demonstrating that weathering had time to disintegrate the surface of one flow before another took place. In western India are similar lava fields, known as the Dekkan flows, two hundred thousand square miles in extent and over a mile thick in places.

It can be understood that such transference of material from the inside of the earth to the outside constitutes at once the grandest and the most important part of the extrusive phase of vulcanism. Volcanoes of the explosive type are often terrible in their destruction of man and property; in many cases they have been locally important in building up the lands and the deep-sea troughs. Their importance as agencies of earth deformation, however, must always stand a poor second to extrusion through fissures, whereby the entire surface of great areas both above and below the sea has been changed.

Effects of vulcanism. We have seen how earth movements deform the outer crust of the earth and interfere with the orderly degradation of the continents by erosion. Vulcanism too deforms the earth's surface, but, unlike diastrophism, whose movements may elevate or depress great segments of the outer shell, volcanic agencies nearly always upbuild. Vulcanism, therefore, and extrusive vulcanism especially, is a great means of surface reconstruction and a powerful enemy of erosion. Constructive work accomplished by vulcanism, unlike the constructive results of normal surface agencies, is forced on the surface from the world below. The results are therefore deformative, in the sense that they are forced on the surface in spite of all that the subaërial instruments of geological change can do to prevent it. Vulcanism comes as a giant from the underworld to undo and deform, as it were, in a moment, the results of the age-long struggles of surface forces.

Volcanic deposits carry with them the exotic flavor of their subterranean place of origin. They are foreigners in a strange land, conspicuously set apart from the formations produced entirely by surface agencies. These deposits may be classified as (1) the materials deposited near the volcanic vents and (2) those which are erupted or which flow to find lodgment at some distance from their place of debouchment.

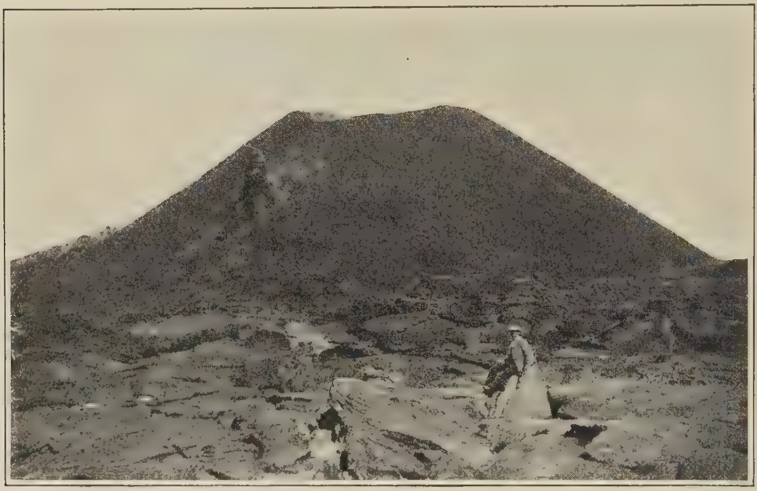

FIG. 102. Vesuvius, a volcanic cone, showing the cone of fragmental materials in the background, and a lava flow, once liquid, in the foreground. (Courtesy of the United States Geological Survey)

Note the parasitic cone on the flank of the main cone

Structure of volcanic cones. Only where volcanic vents are built up above the surrounding country are the deposits of the first group distinguishable from those of the second. Where volcanoes build cones out of some of the material spewed from their vents, the openings through which the liquid rock is conducted to the surface are ducts, or small fissures, of local extent.

Cones of this sort vary with the nature of the erupting material and the violence with which it is forced to the surface. Cones built largely from fragmental material, dust and ash, blown out of the vent with explosive force and settling as solid pieces, are always steep because the angle of rest for such rough angular rock is high. Cones built up by the solidification of fluid lava are steep if the lava was viscous; they are flat and low if the lava was highly fluid. Most volcanic cones are the result of the combined deposition of fragmental and fluid material around vents and are midway between the two extremes of form. Volcanic cones may be beautifully symmetrical in profile, like that of Fuji in Japan; more often they are disfigured, as in the case of Etna, by the growth of small parasitic cones on their flanks. The opening, or crater, in a volcanic cone, from which the ejecta issue, is commonly steep-walled and large if the last eruption was violent, but slopes more gently if much ash and dust fell back into the crater after the eruption. One of the largest craters known is that of Cotopaxi in Ecuador, which is half a mile across and fifteen hundred feet deep.

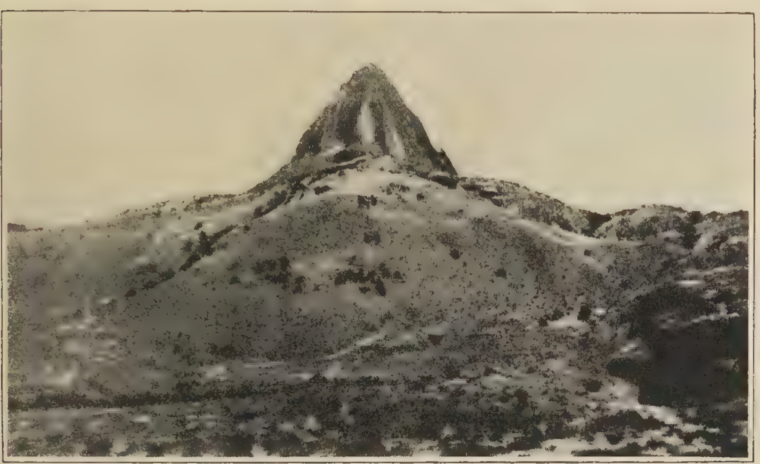

FIG. 103. A volcanic neck, New Mexico. (Photograph by Dutton. Courtesy of the United States Geological Survey)

Volcanic cones, like everything else on the earth's surface, are attacked by erosion. Volcanoes long extinct and subjected to prolonged erosion are deeply furrowed. The solidified magma in the central conduit shows superior power to resist the wear and tear of erosion and is the last to disappear. In certain localities the so-called *necks*, or *plugs*, of extinct volcanoes stand out conspicuously after the looser, weaker parts of the cone have been entirely removed by erosion (Fig. 103).

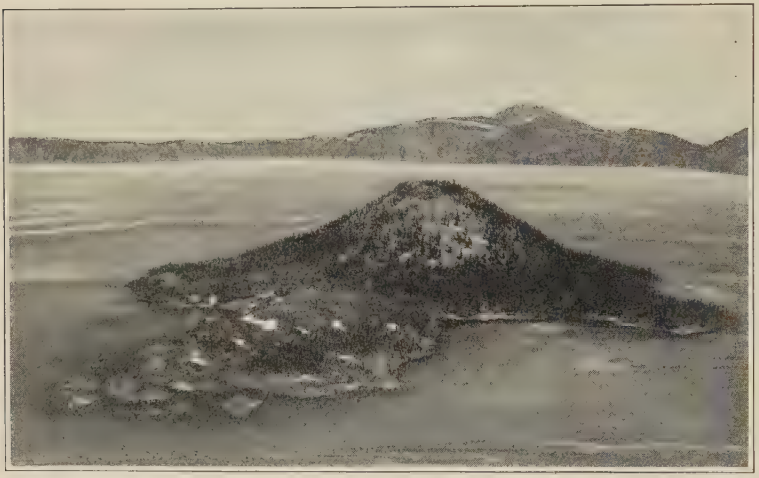

FIG. 104. A caldera, Crater Lake, Oregon, showing Wizard Island, a younger volcanic cone, in the foreground. (Courtesy of the Patterson Studio, Medford, Oregon)

Among the most striking surface effects of vulcanism are the great caldrons, or *calderas*, which are formed either where intense explosion blows the head off a cone, as in Vesuvius and Krakatoa, or where the sides of a crater have caved in and subsided, as in the case of Crater Lake, Oregon. Many giant calderas, several miles across, are known in various parts of the world. If their origin has been through explosion, the surrounding country gives proof of the fact in accumulations of volcanic ash. The volcano at whose summit lies Crater Lake has no loose volcanic débris on its sides and is trenched by glaciated valleys which are cut off abruptly at the edge of the caldera, indicating that the basin originated through sinking rather than through explosion. After the subsidence had occurred, a weak attempt at renewed activity is shown by the presence of a small cone within the crater, now an island which rises a few hundred feet above the lake level (Fig. 104).

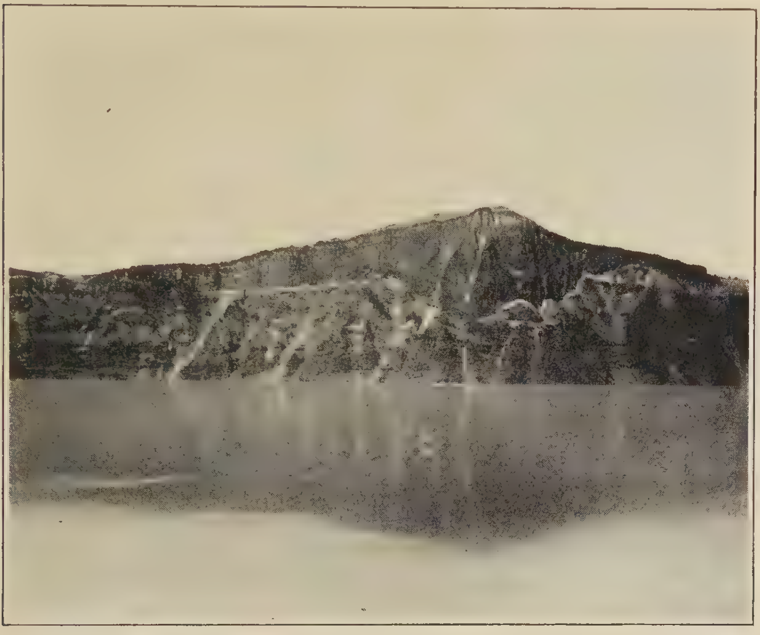

FIG. 105. Part of the rim of Crater Lake, showing a glacial valley filled with lava and cut off by the foundering of the cone. (Photograph by J. S. Diller. Courtesy of the United States Geological Survey)

Materials erupted from volcanoes. Gases and vapors as well as solid and liquid rock are thrown out of the mouths of volcanoes. The gases exhaled by volcanoes enrich the air, particularly the important gas carbon dioxide. Such deadly gases as carbon monoxide and chlorine are known to be given off by erupting volcanoes, but the bulk of the gases thus liberated seem to be comparatively noninjurious to living creatures. Thus, explorers in the Valley of Ten Thousand Smokes, created by the eruption of Katmai in the Alaska Peninsula in

1912, felt no ill effects while living in a region fuming with gases from an untold number of small vents. During the great eruption of Bandai-san in Japan in 1888 a priest dwelling on the side of the volcano lived through the eruption and the gases which enveloped him after more than half the mountain had been blown away. Water vapor in the form of steam is perhaps the most abundantly represented of all the gases or vapors. A French geologist estimated that in a hundred days' observation of one of the small cones on the side of Mt. Etna, more than four hundred and sixty million gallons of water in the form of steam was discharged. It is not yet clearly known how much of the water vapor given off by volcanoes is of deep subterranean origin and how much is ground water turned to steam by the heat of the rising magmas.

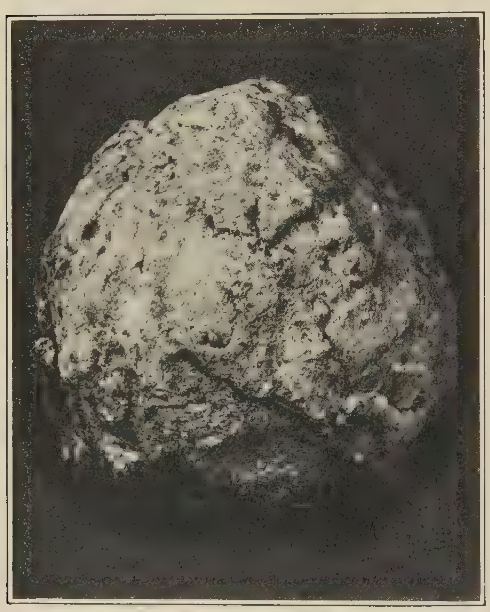

FIG. 106. A volcanic bomb

Large quantities of solid ejecta produced by violent volcanic explosion accumulate after eruption. The magma itself may be blown to bits by the force of its rapidly expanding gases, or parts of an old cone and plug of a former period of activity may be shattered and hurled heavenward. Fragments of rock (for even the liquid magma soon solidifies in the air) thus formed may be so small as to float in the atmosphere for years, or may be rocks that weigh several tons. This material goes by a variety of names, such as volcanic *dust*, *ashes*, *cinders*, and *bombs,* applied according to size (Fig. 106). A not infrequent product of eruption is *pumice,* a rock so full of gas cavities as to be light enough to float on water.

Liquid rock, or lava, does not ordinarily flow from the crater of a volcano until the vent has been cleared of débris by explosion. When the way is clear, lava streams may flow over the rim of the crater or break through fissures on the side of the cone. Fresh lava is red-hot or white-hot; but as it flows, it cools on the surface, hardens, and grows darker. Thick, viscous lava, frothy with gas struggling to escape, may form on the surface of a moving lava stream. This crust may be broken up into a jumbled mass of rough, jagged blocks by the still-moving under part of the flow. Lava fields produced in this way are characterized by the Hawaiian word *aa* (Fig. 108). Nothing is more disastrous to shoe leather than a tramp across a field of aa lava. A new pair of shoes can be completely ruined in the course of a day's walk. Contrasted with the aa lava is that formed from highly liquid magmas and known as *pahoehoe* lava. This is smooth and ropy, with the appearance of a skin inflated with air and then constricted to produce odd twists and wrinkles (Fig. 109).

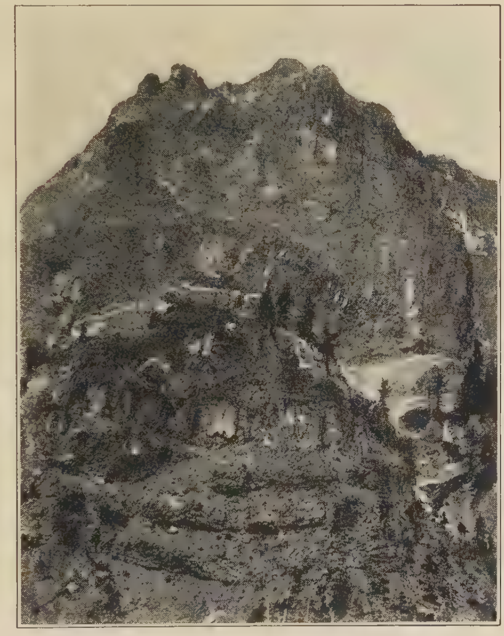

FIG. 107. Successive flows of lava exposed in the rim of Crater Lake, Oregon

Sometimes the lava extruded during the last stages of intense eruptive activity has lost so much heat as to be rendered too viscous to flow. Such lavas pile up in their craters and have been known to form domes of great height. The most amazing example of such a formation was the "spine" of Mont Pelée, on the island of Martinique in the French West Indies (Fig. 110). In 1902 this volcano erupted and projected a prodigious blast of hot air down the mountain side, killing most of the thirty thousand inhabitants of the town of St. Pierre. After the principal eruption a tower of stiff lava began to rise from the crater, reaching in seven months an elevation of a thousand feet. This unusual "spine" was subsequently destroyed by the force of entrapped gases striving to escape and was slowly reduced to a pile of broken fragments. Volcanic domes known in France and Germany are thought to have been formed in somewhat the same fashion.

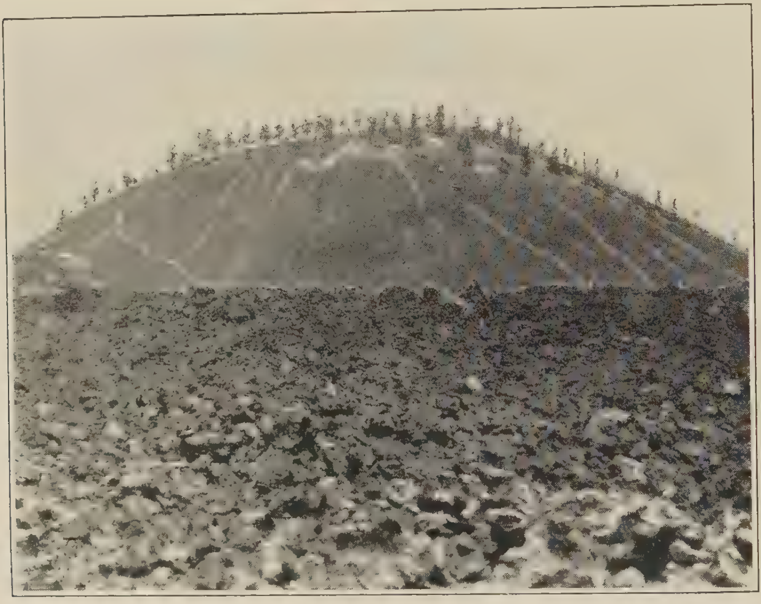

FIG. 108. A cinder cone with a flow of aa lava in the foreground, Lava Butte, Oregon

Distribution of volcanoes. Volcanoes are of gregarious habits: they are not scattered all over the earth, but are grouped in long lines about the borders of continents and in certain limited areas in the ocean basins. The most conspicuous of all volcanic belts encircles the Pacific Ocean, with prominent manifestations along the western coasts of the Americas, from Alaska, Canada, and the United States into Mexico, Central America, and along the Andes to the very end of South America. Thence the line of fire circles round through island chains in the Antarctic to the East Indies, the Philippines, and Japan to complete the circuit in the Aleutian Islands. Another great belt of volcanoes extends in an east-west direction from the West Indies through the Atlantic Ocean to the Azores and other islands to the south, then through the Mediterranean into Turkey and Arabia. Nearly all active volcanoes are situated in one or the other of these two belts.

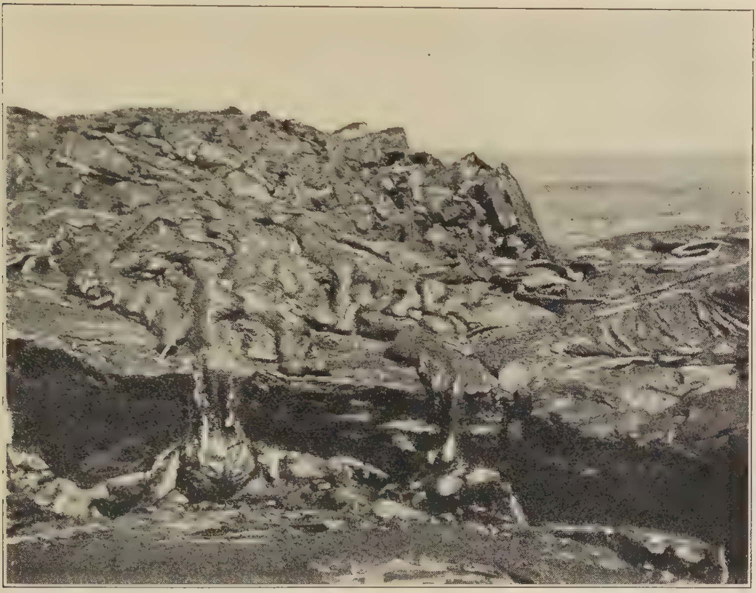

FIG. 109. A flow of pahoehoe lava in the Hawaiian Islands, 1920. (Courtesy of Dr. R. T. Chamberlin)

Some indication of the significance of such alignment can be had when it is seen that the two great volcanic belts are at the same time approximately the two great zones of frequent earthquakes. Regions of volcanic activity are almost without exception parts of the earth's crust which have recently suffered deformation or are being deformed at the present time. Careful study, suggested by the position of volcanoes in lines, has found that volcanic vents tend to group themselves along great lines of instability in the earth's crust, where fractures and folding of the rocks have offered to the struggling magmas of the interior an approach to the surface.

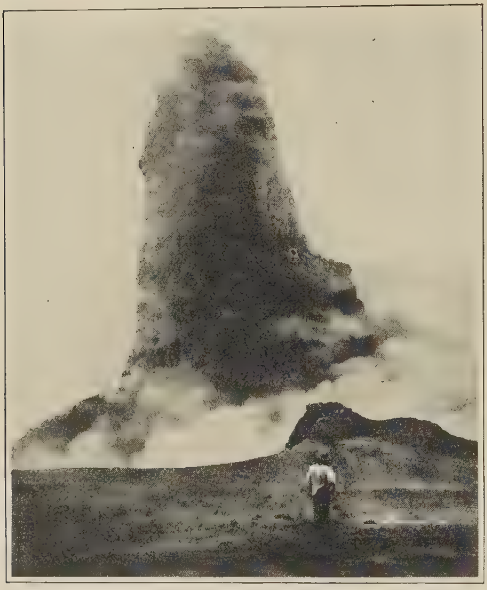

FIG. 110. Spine of Mont Pelée, West Indies, 1902. (Courtesy of Dr. E. O. Hovey and the American Museum of Natural History)

Subordinate volcanic manifestations. Long after an eruption has occurred a volcano may liberate vapor and gas from minor vents in the crater or on the flanks of the cone, and sometimes in the neighboring country. Such emanations are called *fumaroles* (Fig. 111). Where vapors and gases issue through a layer of clay, cones of mud with small craters at their apexes, miniature volcanoes, are sometimes formed. These are the *mud volcanoes*, to be seen in Yellowstone National Park and elsewhere. Fumaroles are remarkably persistent in some regions. The famous volcano Solfatara near Naples erupted in 1198 and has been smoking ever since. This particular emanation gives out much

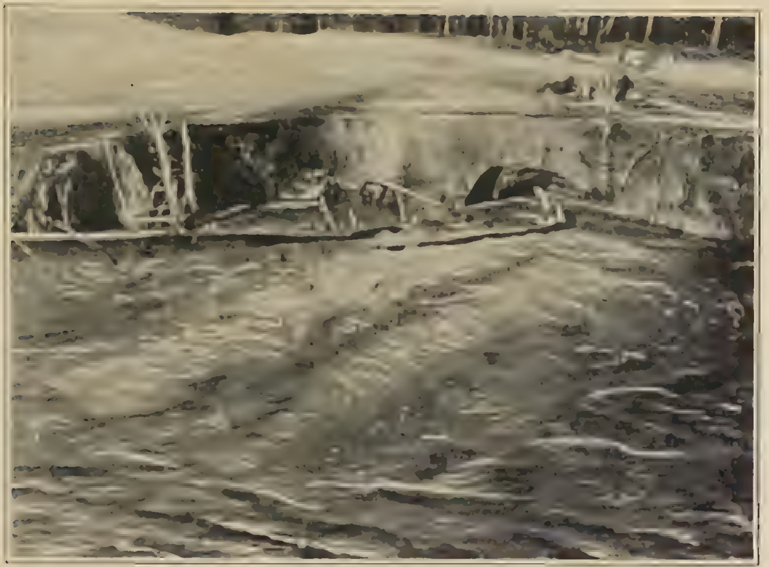

FIG. 111. A fumarole finding a vent through soft clay soil in Yellowstone National Park

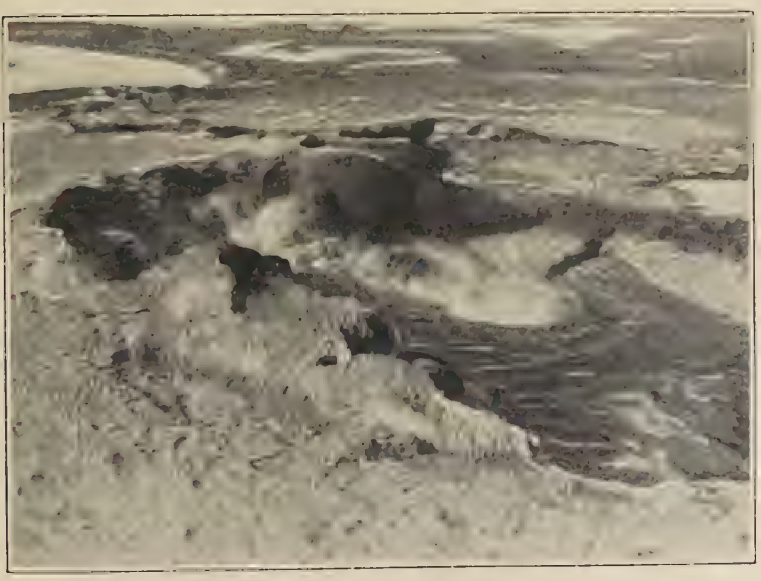

FIG. 112. A hot spring in Yellowstone National Park

sulphurous material, and consequently the term *solfatara* is applied elsewhere to fumaroles which emit vapors heavily charged with sulphur.

Associated also with the waning vitality of volcanic areas are those emanations which are liquid. *Hot springs* are common phenomena in many countries and are caused by ground waters coming in contact with hot rocks below the surface or receiving heat from magmatic vapors passing through from lower depths. The water of such springs may be anywhere from mildly warm to boiling hot (Fig. 112).

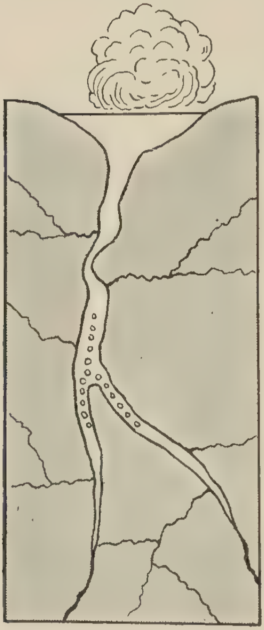

FIG. 113. Diagram illustrating conditions necessary for geyser action. (Reprinted by permission from "Textbook of Geology," by Pirsson and Schuchert. Published by John Wiley & Sons, Inc.)

The most interesting of the minor volcanic phenomena are the gushing hot springs, or *geysers*. Certain conditions must be present in the rocks through which hot springs issue to enable them to erupt intermittently as geysers. These conditions are so rarely present that well-developed geysers exist in but three regions in the world: Yellowstone National Park, Iceland, and New Zealand. Geysers erupt by virtue of the accumulation of steam in a tube of water of unknown length. If a cavity or fissure holding ground water is short enough so that convection currents can distribute heat more or less equally throughout, a normal hot or boiling spring will result; if the cavity is deep and convection impeded, it is possible that the water in the bottom of the tube will be brought to the boiling point before that in the top. Steam then forms in the bottom of the tube, and in working upward forces water out of the top of the tube. This relieves the pressure throughout the tube and allows a great percentage of the water to pass

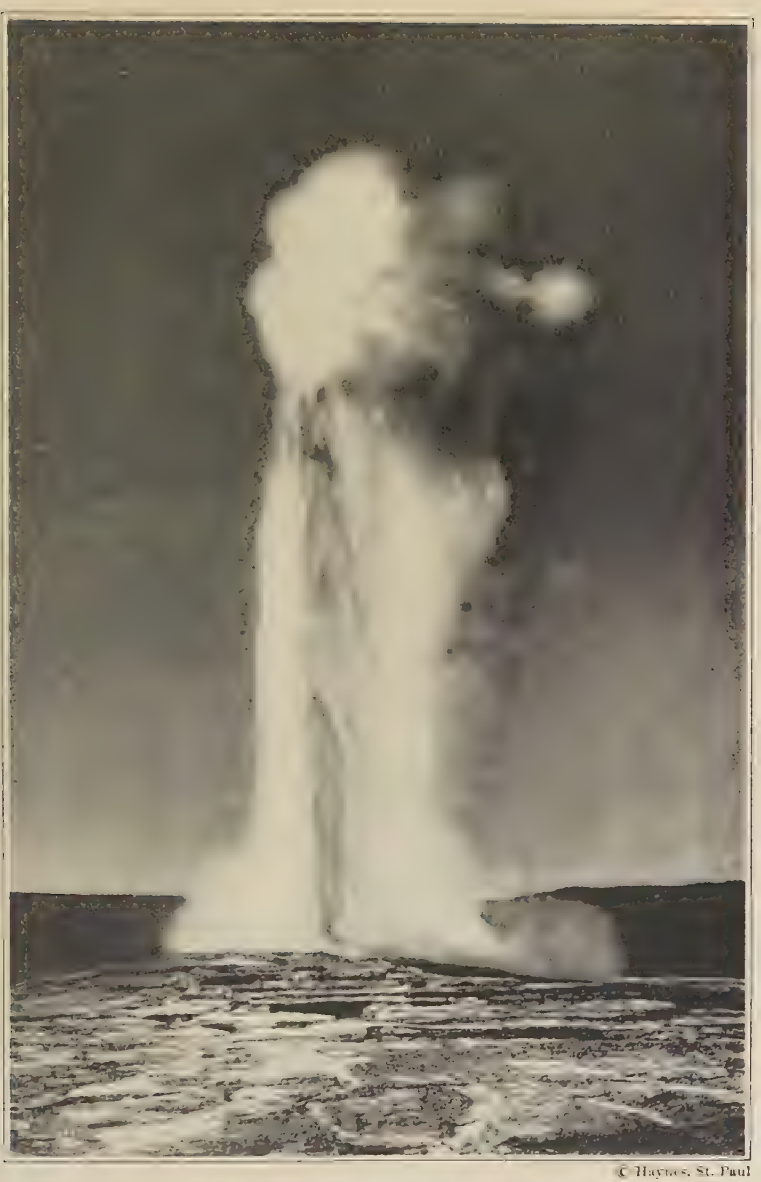

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FIG. 114. "Old Faithful" geyser in eruption, Yellowstone National Park the boiling point and burst suddenly into steam. The abrupt conversion of much of the water into steam causes the eruption. After eruption, ground water slowly refills the geyser tube, and the cycle is complete (Fig. 113). Anything that impedes the distribution of heat in a geyser tube will hasten eruption. Thus, if soap is thrown into the orifice of a geyser, the viscosity of the surface waters is increased, allowing the water below to reach the boiling point long before that at the top, and sooner than if no soapy water were present at the top to retard the transference of heat. The result is a premature eruption. The practice of "soaping" geysers by impatient tourists is no longer tolerated in Yellowstone National Park, because too much soaping causes geysers in time to cease erupting.

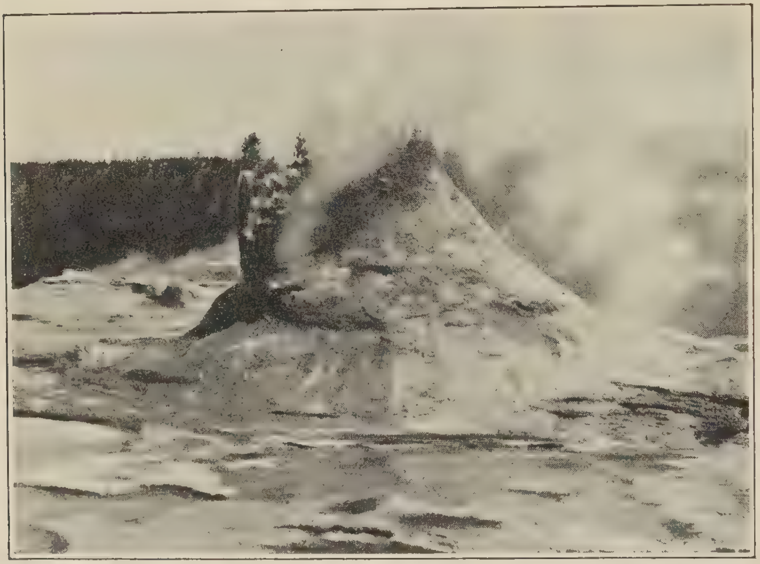

FIG. 115. A siliceous cone deposited at the orifice of a giant geyser in Yellowstone National Park

Such geyser cones are not uncommon

Although some geysers, like Old Faithful in Yellowstone Park, have reputations for regularity of eruption, most are irregular. For this reason they have taken their toll of human life. Formerly the world's greatest geyser, Waimangu in New Zealand, has recently renewed activity after several years of dormancy, but on a smaller scale. At her best, Waimangu hurled a spout of water, black with mud and rock, to a height of fifteen hundred feet. This geyser rises from the surface of a small pond, and because of the treacherous irregularity of eruption and the harmless appearance of the pond during times of quiet, Waimangu has taken the lives of at least three unwary observers.

Causes of vulcanism. We have now reviewed in a broad way the essential facts concerning the surface phases of vulcanism. It remains to ask whence comes the heat which makes the rising magmas possible, whence come the magmas and their included gases, and, above all, why do the magmas rise? These questions depend for their answers on knowledge of a region completely beyond the observation of man — the earth's interior. For this reason it is clear that such questions can probably never be satisfactorily answered.

We have seen that to explain diastrophism it is necessary to assume a cooling and shrinking earth. To explain vulcanism we must assume that at least part of the earth is still very hot. Man has little access to the subterranean place where the energy of vulcanism dwells. The deepest mines, wells, and other man-made borings are mere scratches compared to the radius of the earth, and can give us little information of the vast depths below. It may be a significant fact, however, that in all such artificial excavations the temperature rises with depth. The rate of rise varies greatly in different localities, from 1° F. in less than twenty feet to 1° F. in one hundred and thirty feet. A rise of 1° F. in sixty feet is sometimes taken as a representative average. Assuming that such an average is maintained downward, at a depth of thirty-five miles the rocks would stand at the prodigious temperature of over 3000° F., which is sufficient to melt nearly all kinds of rocks under surface conditions.

We have seen that rocks in the earth's interior are intensely rigid, that even if they are sufficiently hot to be liquefied at the surface under one atmosphere of pressure, under a pressure of thousands of atmospheres they become at least as rigid as steel. This rigidity of the earth is proved by the manner in which earthquake waves are transmitted. The great velocity of these waves, and the fact that waves passing directly through the earth are accelerated below a depth of thirty miles, show the earth to be rigid and to increase in rigidity toward its center. Furthermore, if, according to the old belief, the earth's interior were liquid, it would be pulled out of shape by the attraction of the moon and other celestial bodies passing near it.

It is known from observations with the pendulum and the plumb line that the specific gravity of the earth as a whole is 5.6; that is, the whole earth weighs 5.6 times as much as an equal volume of water. The rocks of the earth's surface, on the other hand, have a specific gravity of 2.8. It follows that the interior of the earth is composed of material at least as heavy as iron, the specific gravity of which is 7.7.

Any theory of vulcanism must be compatible with these three inferences, then: (1) that the interior of the earth is very hot, possibly more than 100,000° F. at its center; (2) that the earth acts as a body at least as rigid as steel, under great pressure within, perhaps as great as three million atmospheres at the center; (3) that the density of the earth, perhaps as a result of increasing gravity, increases from the surface to the center. On this threefold basis of inferential fact many diverse theories to account for the cause of vulcanism have been erected as targets, all of which have been rather badly riddled by a fusillade of criticism. It is not for us to judge these much-mooted questions, but to see what progress, if any, man has made in understanding the earth's interior.

Origin of internal heat. We have seen that by both indirect and direct evidence we know that the earth's interior is hot. Nobody knows whence this heat was derived. One great school of thought believes that the heat was inherited from an ancestral sun so hot as to be largely gaseous, which produced our globe by virgin birth; that the earth has for a long time been cooling from the outside to the inside, leaving the latter with much of its original heat. Another great school postulates a biparental origin for the earth, with a sun for maternal progenitor and as paternal ancestor a visiting body of sufficient size to disrupt the mother sun by close approach and resulting tidal pull. According to this theory the earth is pulled bodily from its mother, and, after a series of changes, grows slowly by the accretion of little planets to its present size — essentially solid from birth; internal heat is only in a small degree inherited, it is gradually developed by the impact of small planetary material and by the contraction and compression of the growing earth through gravity. In an earth conceived in this way heat would not be equally distributed throughout, but would develop in regions of more easily fusible rock and work to the surface by melting out channels of magma locally. Innumerable corollaries to these two most important theses can be found in geological literature, as well as other theories less worthy of mention. Let it suffice to say that whereas the bulk of geologists formerly held the belief in a liquid interior inherited from an ancestral sun, as taught by Laplace, the modern trend of opinion is increasingly in favor of Chamberlin's theory of a solid earth and growth of heat by friction and rearrangement among rocks.

Origin of magma. We have seen that if the earth is composed of a thin outer crust over a liquid interior, then the heat which makes the interior liquid must be derived from an intensely hot ancestral sun. According to this belief magmas rising in volcanic vents or intruded into the outer crust without reaching the surface are but seepages from the vast reservoir of liquid rock comprising all the earth's interior. Since, according to this theory, the magma all comes from one reservoir, all eruptions from adjacent volcanoes should be simultaneous, which of course is not the fact. Furthermore, if a single reservoir were the source of the magma, eruption would take place in the lower of two adjacent vents. Since some existing volcanic outlets are as much as twenty thousand feet below the sea and others twenty thousand feet above, an explanation cannot be found if a single great interior reservoir of magma be postulated. For these and other good reasons this belief has been all but abandoned. Other hypotheses, based on the assumption that the magmas are derived from an original source, answer only part of the objections against the main thesis just sketched and consequently receive little support.

We have seen how Chamberlin, in his theory of earth origin by the slow infall of small planetary bodies on an earth knot pulled from a mother body by the tidal attraction of a visiting celestial body, holds that internal heat is largely the result of compression and friction; magmas develop locally and, by a combination of fusing and fluxing, work to the surface. This interesting hypothesis explains the distribution, periodicity, and many other idiosyncrasies of volcanoes better than any of the older hypotheses, but it leaves to future research the explanation of the sources of the energy necessary to melt rocks and produce large tongues of rising magma. It is too soon for predicting the future of any theory to account for the magmas which are displayed in the processes of vulcanism. At the present time no explanation is without its serious objections.

Origin of subterranean gas. Like the problems of the origin of heat and magma, the origin of the gases present in all magmas is still a debated question. As before, we find opinions grouped around two great nuclei of thought: one arguing that the gases were original possessions of the magma, the other that they have been largely acquired by the magma in rising to the surface. Experiment has proved that all rocks contain gas in large quantities. On the other hand, there is evidence to prove that the water vapor, which is preëminent among the gases associated with magmas, has to a large extent been absorbed by the lava from ground water and the sea as it nears the surface. No decision concerning the origin of volcanic gases has yet been reached, but the bulk of rapidly accumulating evidence seems to favor the belief that the gases were largely primary constituents of the rocks.

Cause of the rise of lavas. Any theory which puts the birthplace of lavas deep within the earth's interior is confronted with the great difficulty of explaining their ascension through such a dense medium as the deep interior of the earth is known to be. Furthermore, most lavas have specific gravities which do not greatly exceed 3.0, so that they should be expected to originate not far below the outer zone of light rocks. Certain reactions, however, may produce lighter rocks at a lower depth, and these may rise to the surface.

The location of volcanic chains along belts of weakness shows that magmas probably utilize as avenues of approach to the surface the faults and fractures which already exist in the upper crust. When magmas reach the weak surface zone of fracture, however, their major work has already been accomplished. The great forces which impel lavas toward the zone of fracture and the means by which they reach this zone are still unsolved problems. Without going further into the theories to explain the rise of magmas, enough has been said to show that whereas some of the factors which generate great energy in the interior of the earth are known, their relative importance, the interaction of one factor with another, and the manner by which they gain their results are still debated points. It seems logical to believe (1) that the earth is deformed by shrinkage, and that great strains must be set up within its body which produce forces that aid in urging magmas to the surface; (2) that the gases dissolved in all magmas, whatever their origin, develop enormous explosive power when pressure on the magma is sufficiently reduced. These forces and other subsidiary ones appear powerful enough to cause magmas to rise, at least from a depth not exceeding fifty miles from the surface. The exact modus operandi of these forces is still awaiting solution.

CHAPTER V

ROCKS AND THE ARCHITECTURE OF THE EARTH

In the preceding chapters we have reviewed some of the larger features of the earth as it appears today, as well as the Titanic forces which have striven from the dim dawn of geological history to alter not only the surface but also the interior of the globe. The science of geology treats not only of the great but also of the small, and in this chapter, which is concerned with the architecture of the lithosphere, we must first consider the small units out of which all geological structures are built. Such units are known as minerals and rocks. A *mineral* is a natural inorganic substance possessing definite physical and chemical properties. Most minerals have a regular symmetrical shape bounded by flat surfaces, and such forms are called *crystals*. Most minerals do not commonly develop their crystal forms, for the reason that crystals grow only under the most favorable circumstances.

Although the number of distinct minerals is great and their crystal forms many, very little variation occurs within a given mineral species. Thus the common mineral quartz, which is composed of silicon dioxide, is essentially the same in chemical form, whether found in Madagascar or in Maine. The fidelity with which minerals adhere to their appropriate characteristics, regardless of the variety of conditions under which they are formed, makes their study the most exact subscience in the entire field of geology.

A *rock* is an aggregate of minerals which constitutes a rather extensive part of the earth's crust. Rarely a rock may consist of but one mineral occurring in great quantity. Since most rocks are made up of two or more minerals, rocks do not have the uniform physical and chemical make-up which characterizes minerals. Rocks tend to grade from one type into another, with scarcely perceptible variation, so that the endless series of forms found in nature must be rather arbitrarily divided for the sake of classification and discussion.

We have seen how all the rocks of the earth's crust fall into three natural groups, according to their origin. The first of these are the *igneous* rocks, which were formed by the cooling and congealing of hot liquid material; the second of these are the *sedimentary* rocks, originating in the waste of earlier rocks and deposited, for the most part under water, by physical, chemical, or organic means; the last great group are the *metamorphic* rocks, which are igneous or sedimentary rocks that have been profoundly altered by heat or pressure, or by a combination of both, so that their original nature is obscured.

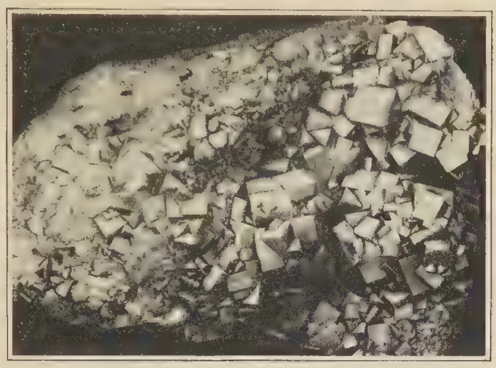
FIG. 116. Cubical crystals of the mineral pyrite

IGNEOUS ROCKS

Igneous rocks are those which have been formed from a liquid condition. They constitute by far the greatest part of the lithosphere, and from these all other kinds of rocks have been derived. On the surface, however, their importance is not everywhere manifested, because of the comparatively thin layer of sedimentary and metamorphic rocks which covers extensive areas.

In our study of vulcanism we have learned something of the habits of rock magmas. We have seen how some of these magmas, in working toward the earth's surface from the deep interior, have cooled and solidified as dikes, sills, laccoliths, and batholiths before the surface was reached. These are the *intrusive* igneous rocks. Other magmas succeed in reaching the surface through volcanic vents, to be laid on the surface as lava flows or as dust and ash. These are the *extrusive* igneous rocks. Let us now inquire into the nature of these two groups and see what natural subdivisions can be recognized in each.

CLASSIFICATION

Igneous rocks are the most difficult to classify because of the manner in which the various kinds grade into one another. On the basis of chemical composition the igneous rocks can be divided broadly into *acid* and *basic* types. The acid igneous rocks are rich in silica (over 65 per cent) and poor in iron, lime, and magnesia. As a result they are light in color, fuse only at very high temperatures, and have a low specific gravity. The basic igneous rocks, on the other hand, are comparatively poor in silica (less than 55 per cent) and rich in iron, lime, and magnesia. As a result they are dark in color, fuse at comparatively low temperatures, and are heavier than the acid rocks. Between the acid and basic types are rocks of intermediate character, which cannot be assigned to one group or the other.

We have seen that the rate of cooling in a magma profoundly influences the appearance of the resulting rock. When a magma cools slowly, as is usually the case with intrusives solidifying below the surface, the rock formed is coarse-grained because the crystals have had time to grow while the original melt was gradually becoming solid; when a magma cools rapidly, as is usually the case with extrusives, the rock formed may have only very small and poorly developed crystals. In some cases the extruded magma cools so rapidly that a glass is formed in which no crystals whatsoever develop. The rate of cooling in a magma largely determines the amount of crystallization in the resulting rock, and this in turn determines the grain, or *texture*, of the rock. Since the texture of igneous rocks is the result of definite modes of origin, a classification based upon this character is logical. Thus we can classify igneous rocks as the *coarse-grained*, the *fine-grained*, the *glassy*, and the *fragmental* varieties.

Coarse-grained rocks. This group contains several subdivisions, of which only five are extremely common. The mineral grains are large enough to be clearly visible to the naked eye. All members of this group were formed by igneous intrusion and were cooled slowly beneath the surface of the earth. Where they outcrop at the surface, erosion has removed the cover of overlying material.

1. *Granite.* Granite, one of the most abundant rocks in the earth, always contains two minerals: quartz and feldspar (Fig. 117). *Quartz* is the most resistant of the rock-forming minerals, and it can be recognized by its glassy luster, its irregular fracture, and its transparent white to gray appearance. The *feldspar* grains are opaque and break along two shiny planes of cleavage, which easily distinguishes them from the irregular, transparent grains of quartz. Feldspar is commonly pink, red, white, or gray. In addition to the two fundamental minerals, a granite may possess muscovite, biotite, or hornblende. Some granites have various combinations of these three accessory minerals. Muscovite and biotite are together known as *mica*; they can be readily identified by their very ready cleavage in one direction, along which the minerals may be split into thin, elastic sheets. *Muscovite* is the white variety of mica. *Biotite* is a brown to black variety. *Hornblende* is dark

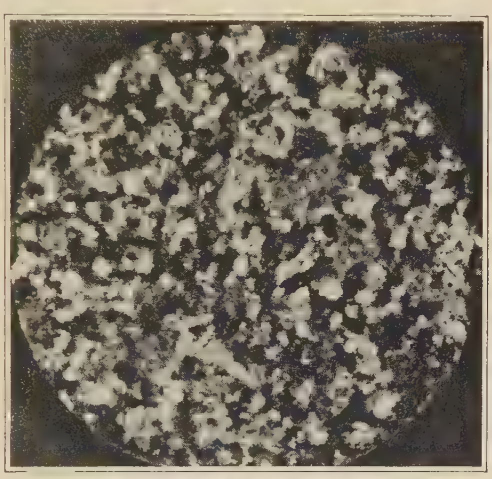

FIG. 117. Granite, a coarse-grained igneous rock

Note the gray quartz, the white feldspar, and the black hornblende green, brown, or black; it can be recognized by its two good planes of cleavage and by the needlelike or bladelike crystals.

Granites are important as stones for monuments and buildings. They go by a variety of names. Thus, the *Barre granites* are named from the locality in Vermont where they are quarried. Such terms as *red granite* or *gray granite* depend upon the general blend of the colors of the constituent mineral grains. If any of the accessory minerals occur in abundance, the granite may be qualified by the name of that mineral, as *muscovite granite, hornblende granite.* If two accessory minerals occur in nearly equal proportions, the rock may be named after both, for example, a *biotite-hornblende granite.* Very coarse-grained granites are called *pegmatites.*

2. *Syenite.* Syenite is very similar to granite and is often marketed as granite. An important distinction between the two is that syenite contains no quartz. Although quartz is missing in all syenites, this group of rocks is rich enough in silica to be classed as an acidic rock.

3. *Diorite.* Diorite is a rock normally composed largely of hornblende and feldspar. In most cases the hornblende predominates, so that diorites are dark in color. In some diorites, however, the place of hornblende is filled by some other dark mineral or minerals. Although diorites have as much silica as syenites, the lime and magnesia content is greater, so that they are more basic than acidic.

4. *Gabbro.* Gabbro is superficially very similar to diorite, the only real difference being that in gabbro the hornblende is ordinarily replaced by the mineral augite. *Augite* is hard to distinguish from hornblende with the naked eye; but it can be told by its two cleavage planes, which intersect nearly at right angles, and by the fact that it forms stubby crystals rather than the long, flat crystals typical of hornblende. The cleavage of augite is characteristically less perfect than is that of hornblende. As in the case of the diorites, no fast rule can be laid down regarding the composition of the gabbros, inasmuch as augite may be absent, and biotite or hornblende take its place.

5. *Peridotite.* Peridotite, composed entirely of such ferromagnesian minerals as hornblende, augite, and *olivine* (a glassy mineral of a green color), is distinguished by its total lack of feldspar. The amount of silica is below 45 per cent, which places the peridotites at the basic end of the chain. Peridotites are of economic importance because they are the only rocks in which diamonds are formed.

Fine-grained rocks. This group contains a variety of rocks which were extruded as lavas on the surface and solidified before any considerable growth of crystals could take place. Certain intrusive bodies contain rocks of this texture, especially thin dikes and sills, which, on account of their small size, cooled too quickly for the development of easily recognized mineral grains. In this type of rock very small crystals which are not visible to the naked eye can be detected with the aid of a lens. This group stands midway between the well-crystallized, coarse-grained rocks and the glasses in which not even the microscope can detect the individual crystals.

FIG. 118. Felsite, a fine-grained igneous rock

It is evident that the same magma which gives rise to a coarsely crystalline rock like granite under slow cooling might give rise to a fine-grained rock of totally different appearance under rapid cooling. As a matter of fact, each coarse-grained igneous rock of intrusive origin has its fine-grained extrusive equivalent.

1. *Felsites.* Felsites are light-colored, fine-grained extrusive rocks which correspond in composition to granites and syenites among intrusive rocks (Fig. 118). In some felsites a single mineral attains fuller growth than the other constituents of

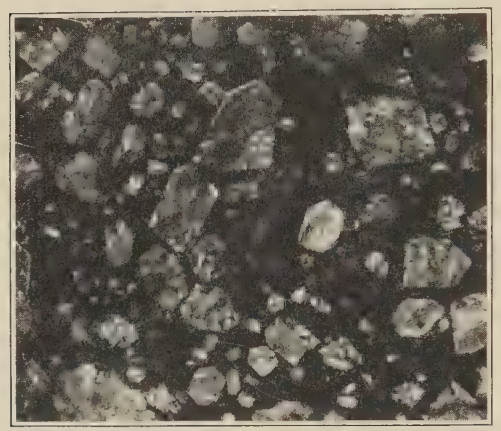

FIG. 119. A felsite porphyry

Note the large feldspar crystal in a fine-grained ground mass

the rock, and its large crystals stand out against a ground mass of fine-grained rock. Such a type is known as a *felsite porphyry* (Fig. 119). Sometimes the porphyritic rock is characterized by the mineral which stands out, as *quartz porphyry, feldspar porphyry.* If the felsite exhibits quartz as the dominant visible mineral, the intrusive equivalent is granite; if feldspar is best developed, the corresponding intrusive rock is most likely a variety of syenite.

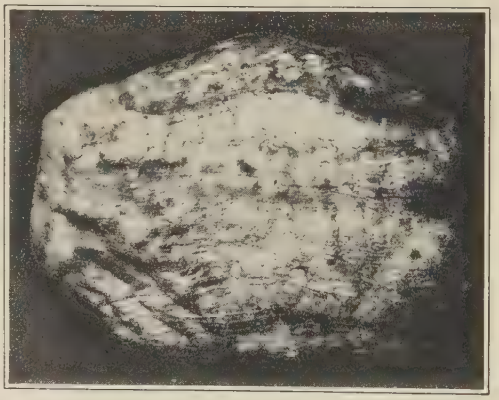

FIG. 120. Flow structure in a fine-grained igneous rock

2. *Andesites.* Andesites constitute a transitional group of extrusive rocks between the lighter-colored felsites and the darker-colored basalts. They are commonly developed among lavas which issue from the central type of volcanoes. The name of this group of rocks is derived from the Andes Mountains, where andesites outcrop at the surface over hundreds of square miles and are perhaps the most common of all rock types.

3. *Basalts,* or *traps.* These are dark-colored, fine-grained extrusive rocks corresponding in composition to the intrusive diorites and gabbros. Like the felsites, this type of fine-grained rock may be porphyritic.

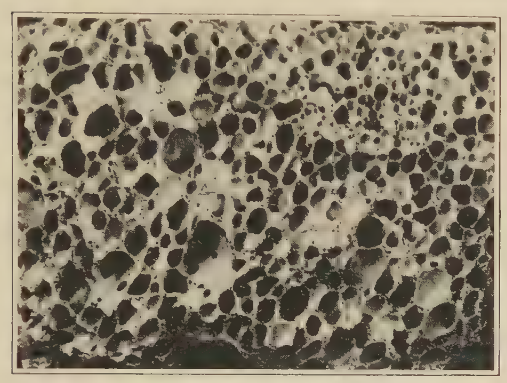

FIG. 121. A vesicular lava

Because the fine-grained igneous rocks were formed almost entirely through the solidification of lava flows, certain detailed structural elements can often be distinguished which make this group of rocks unique. Notable among such are the *flow structures,* rather regular wavy bands formed by the movement of the flow when the rock was still plastic (Fig. 120). In many cases extrusive rocks have an open porous structure due to the expansion of gas bubbles in the liquid rock. Such rocks are said to be *vesicular* (Fig. 121). If the gas cavities have later been filled with mineral matter, the rock is said to be *amygdaloidal* (Fig. 122).

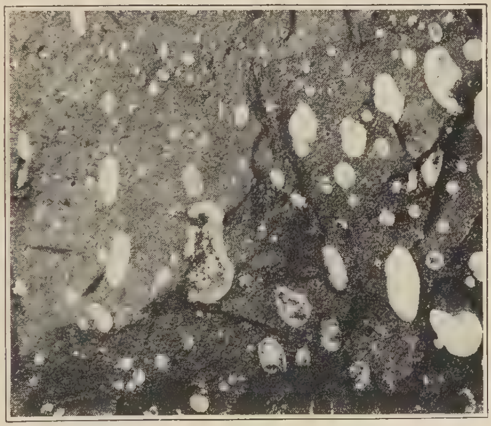

FIG. 122. An amygdaloidal rock

Glassy rocks. Rocks of this group are devoid of crystals and possess a homogeneous, glassy texture. They cooled so rapidly that none of the mineral constituents had time to develop.

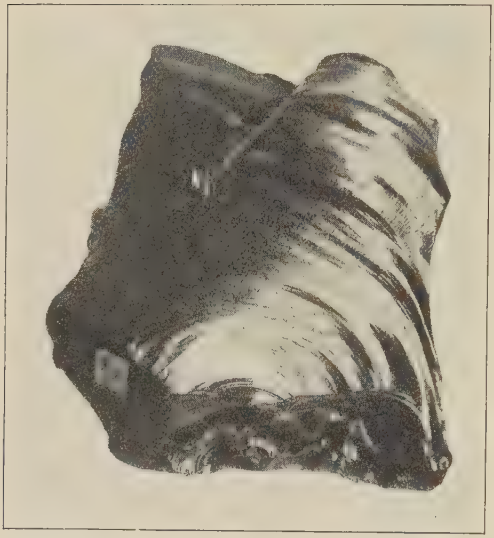

FIG. 123. Obsidian, a typical glassy rock. (Courtesy of the Department of Geology, Harvard University)

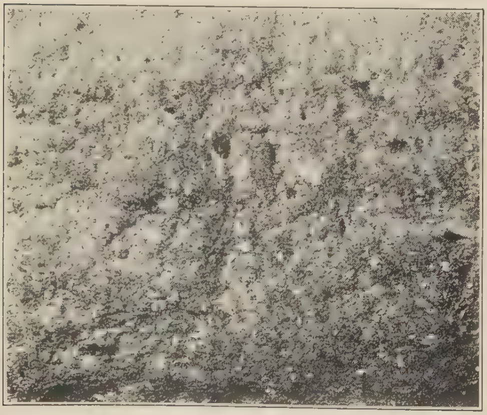

FIG. 124. Tuff, a fragmental rock

1. *Obsidian.* Obsidian is a pure natural glass which breaks with the shelly fracture of artificial glass (Fig. 123). It has a bright luster and is usually jet black, but it may also be gray, brown, purple, green, or red. Obsidian Cliff in Yellowstone National Park is made up of this material, and there are records to show that neighboring tribes of Indians at one time made pilgrimages to collect the rock for the making of arrowheads and knives. Durable and sharp, devoid of planes of cleavage, it is admirably adapted to this purpose.

2. *Pitchstone.* This is similar to obsidian, but is of a duller, more pitchlike luster. The glassy structure is not so well shown in this rock, and small, poorly developed crystals are sometimes present.

Fragmental rocks. Volcanic eruptions, as we have seen, result not only in the seepage of liquid material as lava but also in the formation of various products of explosion. When the material ejected from volcanic vents falls to the earth again, different kinds of rocks, classified according to the size of the particles, are formed. The two following main groups are easily recognized:

1. *Tuff.* Tuff is composed of the finer products of volcanic explosion, dust and ash. It is generally light-colored and is highly porous (Fig. 124).

2. *Volcanic breccia.* This is a coarser fragmental rock composed of angular bits of rock held together by a tuff-like cement of dust and ash. Volcanic breccias contain not only the fragments ejected from the volcano but also pieces of rock torn from the sides of the vent itself.

SEDIMENTARY ROCKS

We have seen how erosion cuts down the rocks of the earth's crust by a varied attack and how the rock waste thus produced is deposited in lake, sea, and ocean. In the beginning all rocks were of an igneous origin, but at the time the earth acquired an atmosphere the work of chemical and mechanical destruction began. Weathering agencies attacked the rocks wherever they were exposed, and abandoned their products to the wind, running water, and moving ice, which, aided by gravity, chemical solution, and precipitation, and by the activities of organisms, transported them to lower levels and eventually to bodies of standing water. From these early deposits the first sedimentary rocks were formed. In like manner, throughout all subsequent geological time to the present, rock waste has accumulated as sediment in the depressions on the earth's surface. In all cases such débris was derived from preëxisting rocks, whether igneous, older sedimentary, or metamorphic.

During the process of transportation and deposition of the diverse materials worn from the rocks, the individual particles of sedimentary material are rounded and sorted according to weight and size. In this way beds of bowlders, gravel, sand, silt, and clay accumulate. Usually such materials are laid down in layers, or *strata* (Fig. 125). It is not uncommon to find strata of fine and coarse materials alternating. This can be explained as the result of variation in the size of the fragments at their source or of fluctuation in the ability of the agents of transportation.

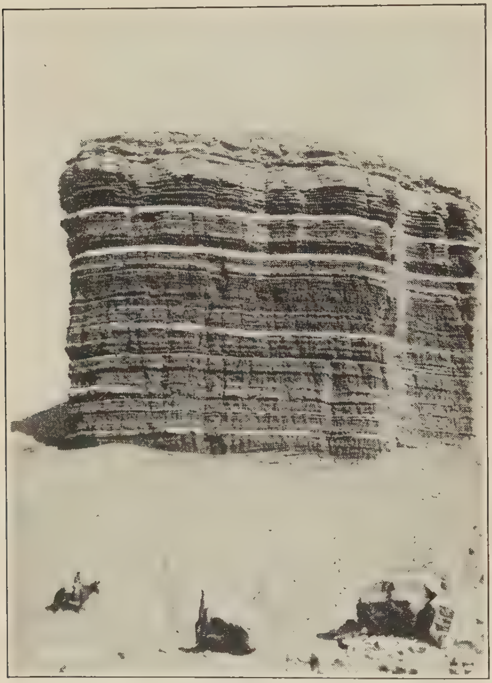

FIG. 125. A cliff of sedimentary rock in Utah showing strata. (Photograph by D. J. Fisher. Courtesy of the United States Geological Survey)

The loose, unconsolidated material is later bound together to form the sedimentary rocks. This is effected by deposition of binding substances between the grains, — ordinarily calcium carbonate, silica, or iron oxide. The process is called *cementation,* and the so-called "cement" is made up of mineral material held in solution by the water, but originally derived from the rocks by chemical attack. A few sedimentary rocks are entirely composed of minerals chemically precipitated from sea water. Such rocks ordinarily lack any cementing substance: they were consolidated by the interdigitating of crystals during formation. A few sedimentary rocks were consolidated without the aid of cementation or crystallization, merely by compression of the particles due to the weight of overlying sediments deposited at a later date. Still more rarely the sedimentary materials may persist for many long ages without becoming consolidated. As a rule, the older the deposit, the more completely compacted and cemented it is. There are notable exceptions to this rule, however, in recent rocks that are well consolidated and very old sediments that remain in much the same loosely knit condition which characterized them from the beginning.

Sedimentary rocks fall naturally into three great groups, based on their origin as mechanical, organic, or chemical sediments. These groups include an almost limitless series of mineral combinations of which, as in the case of the igneous rocks, only the most common and important ones are discussed here.

Mechanical deposits. These are the commonest of all sedimentary rocks. They are composed of the cemented fragments derived from the wear of other, older rocks. Two subdivisions of this group may be recognized: the *siliceous* type, made up of consolidated sand or gravel, and the *argillaceous* type, composed of clay or mud sediments.

1. *Sandstone.* Sandstone is a rock made of grains of sand held together by some cementing material. Sand grains are nearly always composed of small bits of quartz crystals, more or less rounded in the process of transportation. The size of the grains depends upon the distance from the source of supply and the power of the water currents, which are the usual means of transportation. The color of sandstones depends largely upon the binding mineral: if the cement is lime or silica, the sandstone is white or gray; if it is iron oxide, yellow, brown, or red colors predominate. Sometimes dark-gray or black tints are imparted to rocks by the presence of carbonaceous substances. Sandstones are characterized by the nature of the cementing material, as *calcareous sandstone, siliceous sandstone. Arkose* is a sandstone that contains a large percentage of feldspar. This rock is derived from granite and was consolidated before the original grains had been transported far. As a result the easily destroyed feldspar grains and in some cases the mica and hornblende of the original rock are pre-

served. Some arkoses closely resemble granite, but the worn grains of the former ordinarily bespeak their sedimentary nature.

2. *Conglomerate.* Conglomerate is a gravel cemented by finer material. It resembles a sandstone except that the fragments are larger and vary more in size (Fig. 126). Unlike sandstones, conglomerates are characterized by the kind of material constituting the bulk of their pebbles, as *quartz conglomerate, limestone conglomerate.*

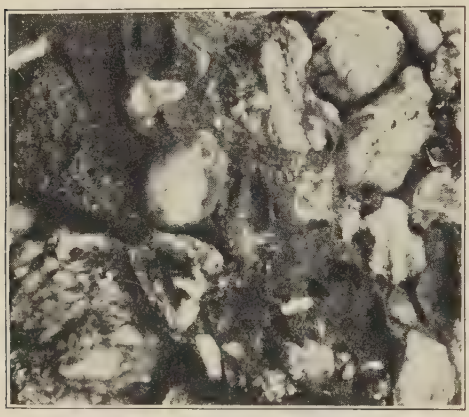

FIG. 126. Conglomerate, a mechanical sedimentary deposit

3. *Shale.* Shale is the rock formed by the compression or cementation of the finer bits of rock waste, known as clay or mud. Shales are normally finely stratified and readily split into thin layers. They are seldom pure, and are characterized by the most abundant foreign element they contain, as *sandy shale,* or by the nature of the cement, as *calcareous shale.*

Organic deposits. This group of rocks owes its existence to materials which were built up by living creatures, or to the accumulated skeletons of living creatures. Organisms are instrumental in the formation of rocks high in (1) lime, (2) silica, (3) carbon, (4) iron, and (5) phosphate. Of these the lime, or calcareous, rocks are by far the most abundant.

1. *Limestone.* Limestone is composed largely of calcium carbonate, but there is a wide range of variations in regard to size of crystal grains, hardness, color, and purity (Fig. 127). In limestones which show their organic nature best, fossil shells of ancient marine creatures are common. In most limestones the microscope is necessary to show their organic

nature clearly. Nearly all limestones are of marine origin, and form best where the earthy material brought to the ocean by streams is lacking. As a general rule, limestones form in the deeper offshore waters, but this is not always the case.

2. *Dolomite.* Dolomite is a limestone made up of particles of calcium carbonate and magnesium carbonate in varying proportions. It is normally of a white, yellow, or gray tint and is harder and coarser grained than ordinary limestone. Dolomites, like limestones, occur widely and are among the commonest of sedimentary formations.

3. *Chalk.* Chalk is a very soft, whitish limestone made up almost wholly of the shells of microscopic animals (Foraminifera).

4. *Carbonaceous deposits.* These are truly organic sedimentary rocks. The stages in their formation are sketched on pages 123–124. Carbonaceous deposits, in general, are composed almost entirely of the remains of plants and animals accumulated under shallow, swampy waters. *Peat* is a partly carbonized deposit of vegetable matter, soft and porous, dark brown or black; the total carbon in it ranges up to 60 per cent. *Lignite* is more compact and harder than peat, dull or bright brown and black, and contains up to 70 per cent of total

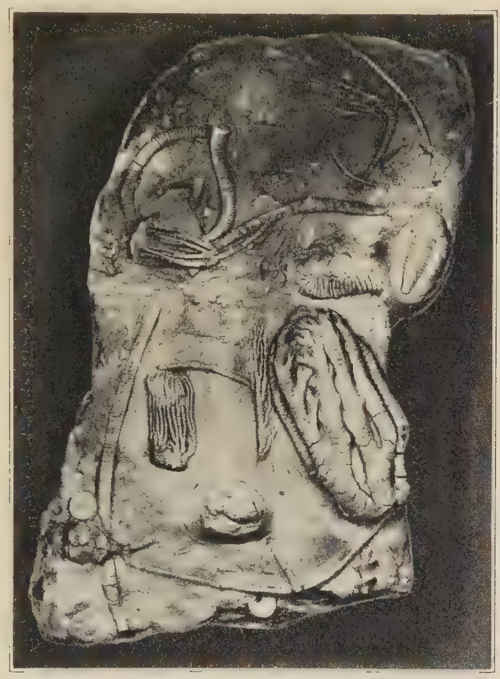

FIG. 127. Limestone, an organic deposit, showing the fossil shells of marine creatures. (Specimen in Walker Museum, Chicago)

carbon. *Bituminous coal* is still harder and more compact, with a brilliant black appearance and from 70 to 85 per cent of total carbon. *Anthracite* is a dense, hard, black rock with brilliant luster and contains from 85 to 98 per cent pure carbon.

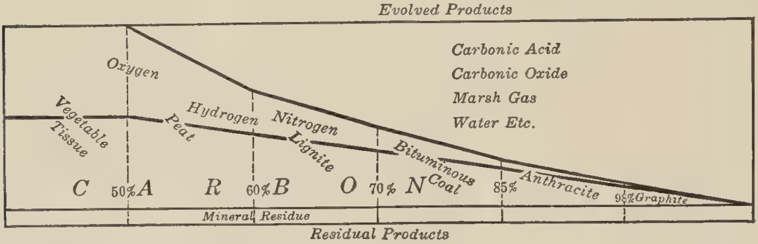

FIG. 128. Diagram illustrating the passage of vegetable tissue into the carbon minerals. (Modified from Kemp)

5. *Siliceous deposits.* This group of rocks is made up of nearly pure silica derived from the skeletons of organisms or deposited through the aid of the life processes of organisms. Among the most important are *flint* (gray to black) and *chert* (white, yellow, pink, or light gray) (Fig. 129). Flint and chert occur as nodules in strata of limestone rock, many of which preserve the skeletal elements of sponges (spicules). Sponges were the organisms chiefly responsible for the origin of this type of rock.

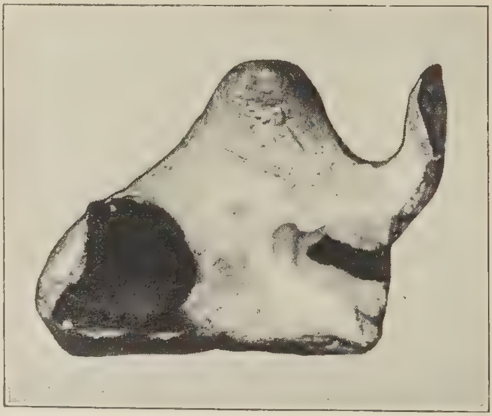

FIG. 129. A flint nodule from the Dover chalk cliffs, England

In addition to the above, certain iron and phosphate rocks of rarer occurrence were deposited through the agency of living things.

Chemical deposits. The rocks of this group are the least extensive of all sedimentary deposits. The material which forms them had formerly been in solution, but because of the concentration of the waters part of their mineral burden fell to the bottom as a chemical precipitate. Such concentration occurs in bodies of water where evaporation exceeds inflow. Fresh-water lakes in arid regions, and arms of the sea which have been separated from the open ocean by diastrophic movements, are the ordinary loci of accumulation for such deposits. Some limestones and dolomites, as well as some flint and chert, seem to have formed in this way. *Gypsum* (hydrous calcium sulphate) is deposited from salt lakes and lagoons, as is *rock salt* (sodium chloride), and is never precipitated except from exceedingly dense brine. Certain iron ores are likewise the result of chemical precipitation in concentrated sea water.

METAMORPHIC ROCKS

Metamorphic rocks are produced when such great heat and pressure are applied to igneous or sedimentary rocks that the original minerals are recrystallized and the original rocks changed in texture and structure. In texture metamorphic rocks resemble intrusive igneous rocks and may be fine, medium, or coarse grained. In structure this group falls into two natural subdivisions. The first is comprised of massive rocks that are homogeneous in the size and arrangement of the parts; when they are broken, the fracture surface is irregular. These rocks are sometimes called *nonfoliated*. Other rocks when metamorphosed split readily along definite planes and are said to be *foliated*. The degree of metamorphism in rocks may vary, but no rock is properly considered metamorphic unless a partial or complete alteration of mineral composition has been effected. Strictly speaking, any change in the mineral composition of the rock is a metamorphic change, but ordinarily the term is restricted to those changes resulting from heat, pressure, or replacement under conditions of relatively high temperature and pressure. A common type of metamorphism is that which occurs where an igneous intrusion penetrates beds of sedimentary rocks. Under such a condition the sedimentary formations are apt to be greatly altered at the contact with the igneous mass, and recrystallization is effected in the sedimentary beds through the heat and gaseous emanations given off by the invading igneous body. This process is called *contact metamorphism.* Sometimes in regions of intense diastrophism lateral pressure and great igneous intrusions so crumple and contort rocks that their form is changed. Rocks of this type underlie extensive areas, and the process by which they were produced is known as *regional metamorphism.* It is difficult to imagine hard, resistant rocks flowing as if plastic under the stimulus of great heat and pressure. Such, however, is the case, and in places rocks which formerly were made to flow like stiff molasses can be seen. It is known further that the sheer weight of thick sediments can produce molecular changes which result in a recrystallization of the underlying rocks. Such metamorphism is known as *static metamorphism.*

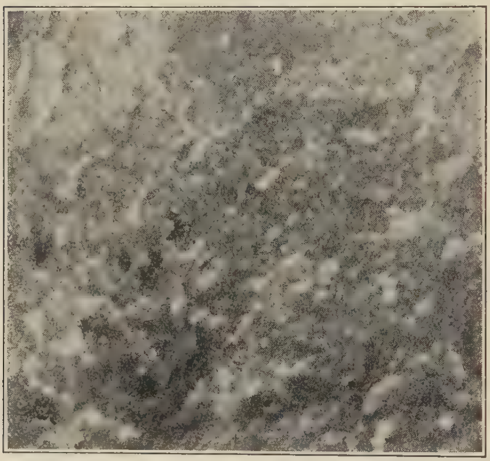

FIG. 130. Marble, a nonfoliated metamorphic rock

It is often difficult to ascertain the nature of the rock before metamorphism took place. The nonfoliated rocks ordinarily give better evidence of their former condition than do the foliated rocks. The following classification includes only the common and easily recognized metamorphic rocks.

Nonfoliated rocks. 1. *Marble.* Marble is a metamorphic limestone. It can be distinguished from limestone by the larger size of the crystal grains of which it is entirely composed (Fig. 130). Marble is always characterized by this granular texture, although a wide variation from fine to coarse grains occurs. The color of marble depends on the impurities present: pure marble is white or buff, such as that from the famous Carrara quarries, in northern Italy; clouded or veined marbles are rendered so by crystallization of the impurities in the original limestone. Marble never breaks into leaves or plates. It is widely used as a decorative stone.

2. *Quartzite.* Quartzite is a metamorphic sandstone. It is dense, very hard, and resists the attack of erosion better than any other rock. It is composed of quartz grains cemented by silica. It is less porous than sandstone, and since it consists of silica throughout, when broken it fractures *through* the grains as well as around them. When ordinary sandstone is broken it fractures *around* the grains only, because the cement is weaker than the particles of quartz sand. The surface thus produced is rough and unlike the smooth surface presented when quartzite is broken. Like marble, quartzite is of massive structure and breaks irregularly.

Foliated rocks. 1. *Slate.* Slate is a metamorphosed shale. It is always fine-grained and dense. Because of the property known as *slaty cleavage,* slates break into thin, smooth plates suitable for roofing purposes. Slates vary in color from gray, which is the most prevalent, to red, purple, or green.

2. *Gneiss.* Gneiss is any coarsely laminated metamorphic rock which resembles granite in composition. Gneisses are usually characterized by the most conspicuous dark mineral present, as *hornblende gneiss, biotite gneiss.* Although the term *gneiss* is applied to metamorphic rocks of widely different origin and appearance, the most common variety roughly resembles a granite in which the quartz and the feldspar have been drawn out into layers that are separated by layers of hornblende, mica, and, in some cases, other minerals (Fig. 131). This *banding,* due to the segregation of light and dark minerals in crude layers, is the most characteristic feature of a typical gneiss. In such the relationship with granite is ordi-

narily clearly shown, and some gneisses are obviously transitional to the unmetamorphosed granite. Gneiss may be derived, however, from coarse-grained sedimentary rocks as well as from igneous rocks of finer texture than granite.

3. *Schists.* Schists grade into gneisses, but are typically more finely foliated. Under intense heat and pressure such minerals as mica and hornblende are flattened and lengthened in parallel planes developed at right angles to the direction of compression. Such surfaces are abundant in a schist and render the rock cleavable into many thin plates. These plates are thinner and more irregular than the flat laminæ developed in slates and known as slaty cleavage. Like gneisses, schists are named from their most conspicuous minerals, as *mica schist, hornblende schist.* Nearly all types of sedimentary and igneous rocks become schists if sufficient heat and pressure be applied. In most cases it is very difficult to determine the nature of the rock out of which a schist was formed.

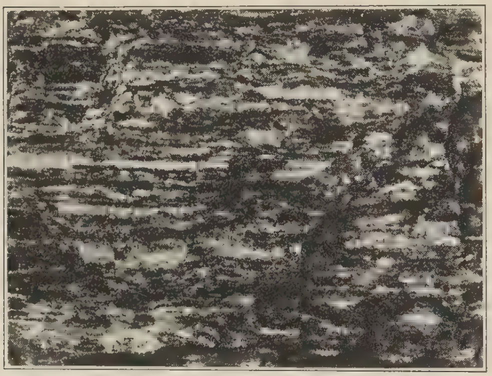

FIG. 131. Gneiss, a foliated metamorphic rock

A general idea of the results of metamorphism in different rock material is given by the following tables, which include only the most abundant rock types:

METAMORPHISM OF SEDIMENTS

UNCONSOLIDATED	CONSOLIDATED	METAMORPHIC EQUIVALENTS
Gravel	Conglomerate	Gneiss and schist
Sand	Sandstone	Quartzite and schist
Clay and mud	Shale	Slate and schist
Lime deposits	Limestone	Marble

METAMORPHISM OF IGNEOUS ROCKS

Original Rock	Metamorphic Equivalents
Coarse-grained acid rocks (granite and syenite)	Gneiss and (rarely) schist
Fine-grained acid rocks (felsite, tuffs, etc.)	Gneiss, schist, and slate
Basic rocks (diorite, gabbro, basalt, etc.)	Schist

STRUCTURE OF THE INTERIOR OF THE EARTH

In the preceding chapter it was shown that little is known concerning the earth below the superficial part of the crust open to direct observation. In a variety of ways certain definite facts of a general nature have been ascertained concerning the deep interior, and upon these a superstructure of theory has been erected which must be considered more as the scaffolding on the structure of truth than as truth itself. In general, it is known that at least part of the earth's interior is very hot, and that the earth is contracting. Studies in vulcanism and diastrophism, as we have seen, amply establish these beliefs as well-grounded facts. How much of the interior heat is original and how much is produced by the pressures involved in contraction or developed by radioactive minerals is still unknown. Furthermore, it is believed that the density of the earth increases from the surface to the center. It is logical to infer that under the insistent pull of gravity during long eras of periodic contraction, heavier material would tend to concentrate nearer the center and lighter materials nearer the surface. There is some evidence to show that this is true — notably in the evidence of earthquake waves, which travel faster through the interior than around the more loosely constituted exterior. The denser the medium, the faster earthquake waves travel. From such evidence it is generally taken that the earth grows denser and more rigid toward its center.

Rock distortion. We have seen that temperatures in deep wells and mines increase with depth. If such an increase in temperature exists everywhere below the surface, it is clear that at some place within the earth there will be a zone within and below which the temperatures are high enough to melt rocks *under surface conditions.* Under intense pressures, however, even highly heated rocks do not easily weaken so as to flow, because their rigidity is increased. Recent experiments by F. D. Adams indicate that rocks suffering the distortional stress of earth contraction, coupled with the weakening effect of high temperatures, do not move about as promiscuously as was formerly believed. For example, if a granite which resists a pressure of twenty thousand pounds per square inch before breaking under surface conditions is buried deeply within the earth's crust, it will not be deformed unless the *differential* pressure applied exceeds the crushing strength plus the rigidity induced by pressure. Let us suppose that the granite is compressed on all sides by pressures of a hundred thousand pounds per square inch. Before distortion can take place the pressure on one side must be increased by more than twenty thousand pounds per square inch (the crushing strength of the rock) plus sufficient pressure to overcome the rigidity induced by deep burial, which strengthens all rocks so confined. It is variously estimated that granites suffer distortion at from seven to eleven

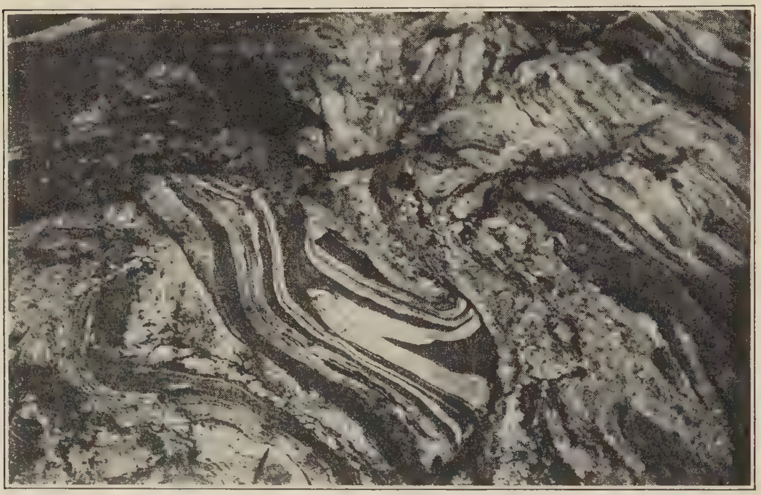

FIG. 132. Rock flow, Massachusetts. (Courtesy of the United States Geological Survey)

miles below the surface. Weaker rock, such as sandstones and shales, are distorted at correspondingly lesser depths.

Rocks are distorted in two ways: by *flow* and by *fracture.* If rocks suffer differential stress under great pressures *from all sides,* the mineral grains are elongated in the direction of least resistance, and the rock is said to flow. The easier type of deformation — by fracture or breakage — takes place where the confining walls about the stressed rock do not exert sufficient pressure to give rise to flowage. The experiments of Adams show that various factors influence the strength of rocks and hence the manner in which they yield to distortional stresses. The slower the deformation, the more resistant to it does the rock become. Rocks which flow under a slowly applied stress may fracture if the stress is applied rapidly, very much as taffy candy can be elongated by pulling, or broken by a sharp blow with a hammer. If for any reason the deformative stresses are interrupted, the rock gains strength and can be said to become rested. Increase in temperature weakens all rocks, and water seems to have an important effect in inducing flow among rocks under differential pressure, but an effect which is not yet fully understood.

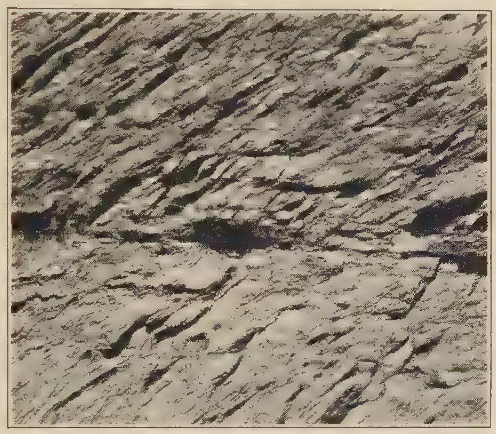

FIG. 133. Rock fracture, Lewis overthrust, Montana

The diagonal cracks were produced by deformation. The horizontal breaks are the bedding planes of the rock and were present before the oblique cracks were developed

It is clear that many factors influence rocks under stress and control the manner in which they yield. For the reasons just stated, for others that are too technical to consider here, and, most likely, for others still undiscovered, it would be unwise to consider the *zone of flow* and the *zone of fracture* as well-marked localities in the earth's crust. The former was once described by a student to be "like heaven, not a place but a condition." In general, rocks under greater pressures and temperatures tend to yield to differential pressure by flowage, and those under lesser pressures and temperatures to yield by fracture, but such is not always the case. It is well known that slate and marble slabs in old tombstones have sagged under no greater pressure than their own weight and under no higher temperature than that of the atmosphere in temperate regions. In these cases the "zone of flow" lies at the surface. Bearing such exceptions in mind, we can proceed safely enough in the general belief that rocks near the earth's surface are deformed chiefly by fracture and rocks farther below the surface by flow; and that at a sufficiently great depth — how great no one knows — all deformation is by flowage.

Strength of the earth's crust. By means of careful observations on the rocks of the earth exposed at the surface and by experiments in the laboratory, the modern geologist has built up a bulwark of evidence around the thesis that the crust of the earth is strong, and not easily deformed. Most of this evidence has been briefly stated in preceding pages, but a summary at this point may not be amiss.

1. The experiments cited above indicate a strength for rocks under stress in excess of their strength under ordinary surface conditions. Since all rocks in the earth's crust suffer stress as the result of the shrinkage of the globe, they are strengthened and not weakened as a result.

2. The rigidity of the earth is proved by (1) the fact that the lithosphere is very little affected by tides and (2) the fact that earthquake waves travel in transverse vibrations through the earth. Since transverse vibrations are not transmitted through a liquid, the earth's interior must be sufficiently rigid to react as a solid. Furthermore, such waves are known to travel faster with depth, which shows that the rigidity of the earth as well as its elasticity increases from surface to center.

3. The study of past earth movements shows that stresses

accumulate in the crust and are yielded to periodically. This proves that the lithosphere is strong, for in a weak earth the rocks would yield to stresses as soon as these were felt.

4. The gigantic piles of thick sedimentary formations localized in the great mountain belts of the world do not materially weaken the earth's crust. More than once in the history of the earth great mountain ranges have been raised and worn down to base level by erosion; this process requires a long time for completion, a long time even as geological time is reckoned. Only a comparatively strong earth crust could uphold such a burden for such a period of time without being markedly deformed.

Isostasy. Although from one point of view the crust of the earth is obviously strong, from another it appears weak. It is strong enough to accumulate stresses to such an extent that sensible movements take place rhythmically, but nevertheless it appears to collapse when it is not supported from below or when it changes significantly from the shape it would take if it were plastic. From observations with the pendulum it has been found that the gravitative attraction of mountains pulls the plumb line away from the vertical. The same thing happens at the juncture of continents and oceans. From these observations it has been inferred that mountains stand higher than the rest of the land because they are made of lighter material. In a similar way continents are higher than ocean basins just as a piece of cork stands higher than the level of the water on which it floats, because it is lighter. From observations with the pendulum in many regions the values of gravity have been determined, and from these data, gathered by many people over a period of approximately fifty years, the *theory of isostasy* has been developed. If in our minds we divide the crust of the earth into segments extending directly down from the surface to the center as apex, then all such segments which occupy equal areas on the surface must have equal weight. Since some parts of the earth's crust stand higher than others, it must be that the tops of the segments comprising the higher areas are of lighter material than that constituting the lower areas. We have seen how erosion is forever shifting material about on the earth's surface, rendering one segment lighter and another heavier. Isostasy postulates that when such transfer of material takes place, as from continent to ocean basin, rock at great depth flows from the heavily weighted segment to the segment from whose top material has been removed. In this way a sort of hydrostatic equilibrium in the earth's crust is established.

Experiments on gravity have shown that the rocks underlying the oceans are heavier than those of the continental masses. The theory of isostasy states that a tendency to equilibrium by underground-rock flowage has been active from very early geological times, and in this way the denser rocks of the ocean basins have been kept lower than the lighter rocks of the continents. According to this theory, then, the continents are like icebergs, and the ocean basins are like the water in which the bergs are immersed.

It is not yet time to evaluate the importance of isostasy in shaping the destiny of the earth. How small the areas sensitive to isostatic adjustments are is yet a debated question among the proponents of the theory. In the early balancing of the outer portions of the globe some sort of isostatic adjustment may well have taken place. Many undoubted geological facts are unfavorable to the acceptance of a belief in an earth which yields as easily to stress as one controlled by isostatic principles must yield. The future alone can show how far this theory is true. It is not unlikely that isostasy will take its place as a factor in earth history more as a secondary process of readjustment following diastrophism than as a major explanation of earth movements and surface relief.

THE SURFACE FRAMEWORK OF THE EARTH

The paucity of known facts concerning the deep interior of the earth is compensated in a measure by a full and growing knowledge of the more accessible portions of the crust. In previous pages the general methods of rock formation and alteration have been discussed. Some of the features of rock structures have been mentioned incidentally, but it remains to scrutinize the formations of the earth's outer crust and their relationships as architectural units in the construction of the planet.

Joints. We have already seen that all the rocks near the earth's surface, excepting the unconsolidated materials of the mantle rock, are traversed by cracks or fractures which divide them into blocks of various sizes and shapes. Such division planes, known as *joints,* are a structural characteristic common to sedimentary, igneous, and metamorphic rocks (Fig. 16). If two contiguous blocks on each side of a joint have been moved apart, or if the opening between them has been widened by solution, the opening is usually referred to as a fracture or fissure. Typical joints do not gape, and the angular blocks which joints produce occupy the same relative position that they occupied before the cracks were developed. If any noticeable movement has taken place along a joint plane, the surface along which displacement has occurred is called a *fault* rather than a joint.

Jointing in igneous rocks. Most of the joints which have developed in igneous rocks can be explained as the result of the cooling and resultant contraction of the original liquid mass. Intrusive igneous rocks, such as granite, are in most cases divided into large prismatic blocks with rather smooth joint surfaces. In rarer instances granite is traversed by joints which separate the mass into rough, sheetlike, horizontally elongated blocks. Such joints are often convex upward, in a curve crudely parallel to the dome-shaped top of the injected body.

The most conspicuous of all types of jointing occurs in the dark, fine-grained igneous extrusives (basalts), and is known as *columnar jointing* (Fig. 134). Rocks exhibiting columnar jointing are divided into columns which are hexagonal or roughly so in cross section. Such prisms are ordinarily crossed by transverse joints very similar to the ball-and-socket articulation of the limbs in mammals. Similar ball-and-socket tension fractures occur when steel is cooled rapidly. The peculiar arrangement of rocks in six-sided columns can be seen in many regions, perhaps best in the famous Giant's Causeway on the north coast of Ireland. In North America the structure can be observed on highways leading west from Spokane, Washington, and over most of northern Idaho. The explanation of columnar jointing is found in the manner in which rapidly cooling rocks lose their heat. In a lava flow of homogeneous nature contraction due to cooling takes place equally throughout the flow. Cracks are developed at equal intervals throughout the mass. The tension produced by contraction is most easily relieved at any given point by three cracks radiating at angles of 120°. Such cracks radiating from many equidistant points in the cooling surface of the flow form hexagonal prisms when they join (Fig. 135). From the surface the cracks penetrate to the interior of the flow, so that the columns always develop at right angles to the surface of cooling. In the same manner each column, contracting lengthwise, is divided by transverse joints. In columns that do not show the regular

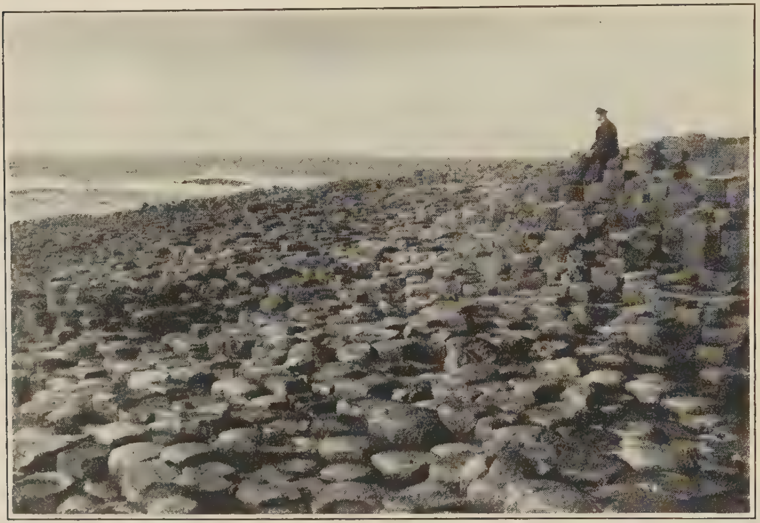

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FIG. 134. Columnar jointing, Giant's Causeway, Ireland. (Reproduced by special permission of the *National Geographic Magazine*)

six-sided cross section some irregularity in the distribution of focal points of contraction under special local conditions may have existed. Columns of four, five, or seven sides are known, but they are less common.

Jointing in sedimentary rocks. We have seen that because of their origin as successive deposits of rock waste most sedimentary rocks are divided into parallel layers known as *strata.* If a single layer in such a stratified rock is thick, it is called a *layer*; and if it is very thin, a *lamina.* Although the usage of these terms is far from standardized, *layer* and *lamina* ordinarily are applied to a section of a sedimentary rock which had accumulated by uninterrupted deposition and within which there are not any natural parallel partings along the plane of deposition. The term *stratum* is used by some in the same sense as layer; by others to characterize a group of layers which, through some property or combination of properties, can be distinguished from layers above and below. Layers, laminæ, and strata are sometimes loosely referred to as *beds.*

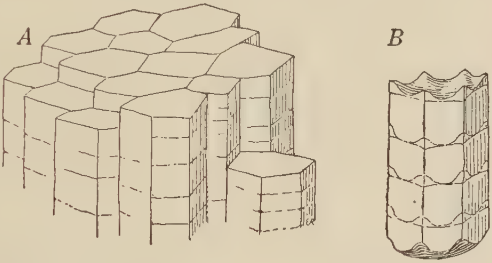

FIG. 135. Diagrams showing (*A*) the hexagonal prisms and (*B*) the ball-and-socket transverse fractures in columnar structure

The important structural feature of sedimentary rocks is that they are divided by natural planes formed at the time the material was deposited. These planes normally mark some change in the conditions under which the rock débris was laid down: a change in the material supplied by erosion, a change in the depth of water in which the materials were deposited, or a lapse in deposition. In undisturbed formations such stratification planes are in most cases horizontal, because the unconsolidated materials were laid down in horizontal or nearly horizontal layers. In rare cases, sedimentary rocks formed under exceptionally uniform conditions show no bedding planes.

Bedding planes in sedimentary rocks are not ordinarily considered joints, since, unlike joints, they did not develop after the formation of the rock but contemporaneously with its formation. In a structural sense, however, bedding planes are in many cases similar to joints. True joints in stratified rocks cleave the bedding planes in but two directions, the third direction of fracture necessary for the separation of blocks being in most cases supplied by a bedding plane. No good classification of joints in sedimentary rocks exists. The nature of the rock itself determines whether the blocks formed by jointing shall be cubical, rectangular, tabular, or any other shape. In thick-bedded sedimentary rocks — in some limestones, for example — the blocks formed by jointing tend to be larger and more regularly shaped than those developed in thinner beds. Certain regularity in the disposition of joints often occurs. Joints which run parallel to a definite direction are known in some areas. Other joints traversing the first set may show equal fidelity to another direction. One set of joints may be developed better than an intersecting set; they may be strongly represented in a great thickness of strata and may be traced over a broad area. Such joints are called *master joints.*

Jointing in metamorphic rocks. Metamorphic rocks share the properties of both igneous and sedimentary rocks. For this reason no characteristic jointing occurs in metamorphic rocks, but, depending on their nature, the joints resemble those formed in the various types of igneous and sedimentary formations.

Origin of joints. An important cause of jointing in rocks is to be found in the movements which have been produced in the earth's crust by stresses developed in the shrinking globe. Another important cause is the tension brought about in the igneous rocks through contraction on cooling and in sedimentary rocks through contraction on drying. Not all features of joints are satisfactorily explained, particularly the smoothness of most joint faces. Joints may be classified as (1) those due to a pulling apart of rocks (*tension*) and (2) those due to a squeezing of rocks (*compression*).

We have already seen that columnar structure in lava flows is due to tension resulting from cooling. Somewhat similar joints are produced by the mere drying of sediments, and this is followed by shrinkage and tension joints. Where the sedimentary rocks have been wrinkled, tension joints often form along the convex crests of the upwarped beds because of the stretching suffered in the wrinkling process. Tension joints are believed to develop in rocks which have recently experienced movement by diastrophic forces. Such rocks are thought to "settle down" after disturbance and to crack under tensile stresses thus produced. Tension joints develop along the faces of cliffs because of the absence of compressive stress on one side.

In some cases the rocks are twisted so as to produce fracture planes known as *torsion* joints. Rocks so twisted fracture in planes at right angles to each other and at 45° with the axis of torsion. Where rocks have been folded by compressive forces, compression joints develop. Likewise, where igneous intrusions have forced their way into sedimentary formations, the latter are squeezed and fractured. The general result of earth shrinkage is compression of the outer rocks in the earth's crust, and compression joints are the most widespread result.

Faults. The study of joints leads naturally to that of faults, because where rocks are displaced along a fracture plane the displacement is called a *fault*. Faults often occur along joints, fissures, and bedding planes, since in such places the rocks have already been weakened. We have seen that rocks near the surface tend to yield to stress by fracturing, because this is the easiest type of deformation. Faulting, therefore, is one of the commonest structural features encountered in the field; in many cases it confuses the geologist in his study of the sequence of events in earth history.

The plane along which rocks have been displaced is the *fault plane*. This surface may stand at any angle of inclination to the horizontal, and the attitude of fault planes is described by measurement of this angle, which is known as the *dip*. The complement of this angle is the *hade*, the angle made by the fault plane with the vertical. Faulting may occur in all types of rocks, but it is more easily recognized and discussed in connection with stratified rocks. If stratified rocks are displaced along a fault plane, the side on which the beds have moved upward and stand at a higher level is known as the *up-throw side*; the other side, on which the beds have moved downward and stand at a lower level, is called the *down-throw side.* Because of the inclination of a fault plane, the rocks on one side overhang those on the other; the side which overhangs is the *hanging wall,* and the opposite side is the *foot wall.* Faulting in stratified rocks separates each stratum affected in a vertical direction as well as a horizontal one. The vertical displacement between the ends of a stratum separated along a fault plane is called the *throw* of the fault; the horizontal displacement is known as the *heave.* The distance between the severed ends of a stratum measured along the fault plane is known as the *slip* (Fig. 136).

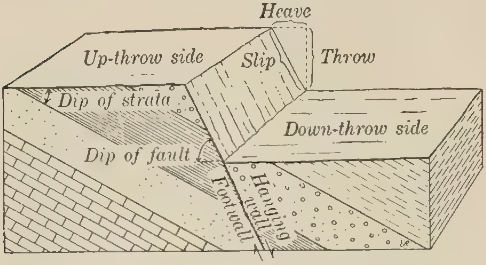

FIG. 136. Diagrammatic section of a normal fault showing the space relationships

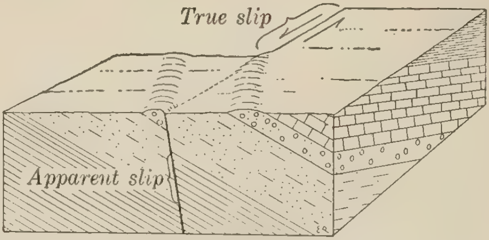

FIG. 137. Diagram illustrating how horizontal movement on a fault plane may appear as vertical movement

Note the true and the apparent slip

The apparent up-and-down displacement of beds along a fault plane is not always produced by vertical movements, but may be the result of horizontal movements, as illustrated in Fig. 137. In applying the terms *up-throw* and *down-throw,* only the relative levels at which the displaced beds stand on each side of the fault plane are taken into consideration and not the actual direction of movement along the fault.

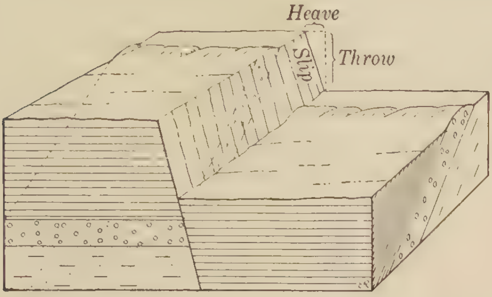

FIG. 138. A normal fault before erosion

Normal faults. The simplest of all faults are those in which the hanging wall has slipped down or has appeared to slip down with reference to the foot wall (Figs. 138, 139). In such *normal faults* the foot wall may have remained stationary or it may have moved up with reference to the hanging wall. We have already seen that faulting may be produced by movements entirely in a horizontal direction, and that the *apparent* vertical displacement does not indicate the true direction of movement. Nevertheless normal faults, which are also known as *gravity faults*, are thought of as the results of vertical displacement controlled by the insistent force of gravity. Although most normal faults are undoubtedly the results of vertical displacement, it should be remembered that some can be, and undoubtedly are in many cases, the results of horizontal or oblique displacement.

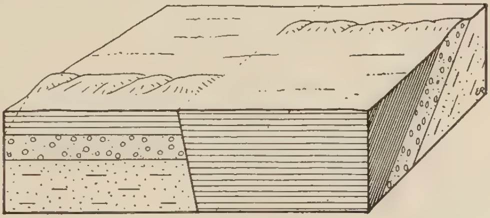

FIG. 139. The normal fault shown in Fig. 138 after erosion

Normal faults may involve displacements of less than an inch to several thousands of feet. They may be of small local extent or be traceable for many miles, in some cases for hundreds of miles. In some regions great blocks of rock have sunk with reference to the surrounding rocks. These blocks, bounded by normal faults, are called *grabens* (Fig. 140). The Rhine valley occupies such a structural depression, and offers a good example of the great influence certain geological features exercise on the history of mankind. The Rhine graben in presenting a natural dividing line between the peoples of central and western Europe performed no little part in the estrangement of the French and German nations. The reverse of a graben, where a block has been elevated with reference to the surrounding rocks and separated from them by faults, is known as a *horst* (Fig. 141).

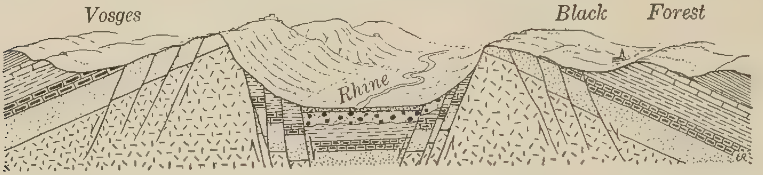

FIG. 140. Diagram showing the structure of the graben of the Rhine valley

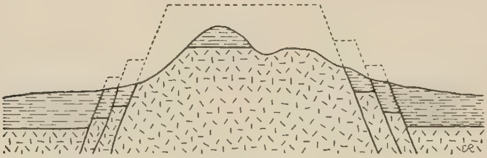

FIG. 141. Diagram of a horst

A section across the Horstgebirge, Germany

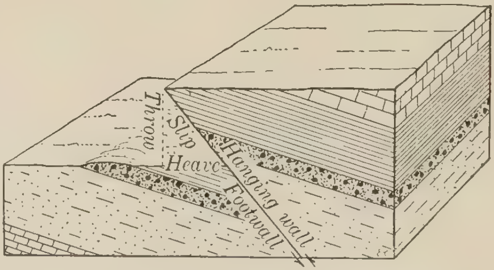

FIG. 142. A reverse fault before erosion

Reverse or thrust faults. In localities where rocks have been crushed, fractures develop along which the hanging wall appears to have moved up the fault surface with reference to the foot wall. This is the reverse of the condition in normal faults, and such dislocations are called *reverse faults* (Figs. 142, 143). When the plane of a reverse fault lies in a nearly horizontal position, the term *thrust fault* is applied. When stratified rocks are subjected to thrust faulting, the underlying beds are occasionally pushed over the top of strata which, previous to the time of faulting, stood much higher. Strong lateral pressures have produced low-angled overthrust

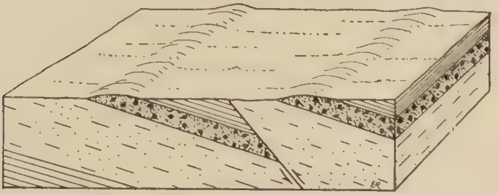

FIG. 143. The reverse fault shown in Fig. 142, after erosion

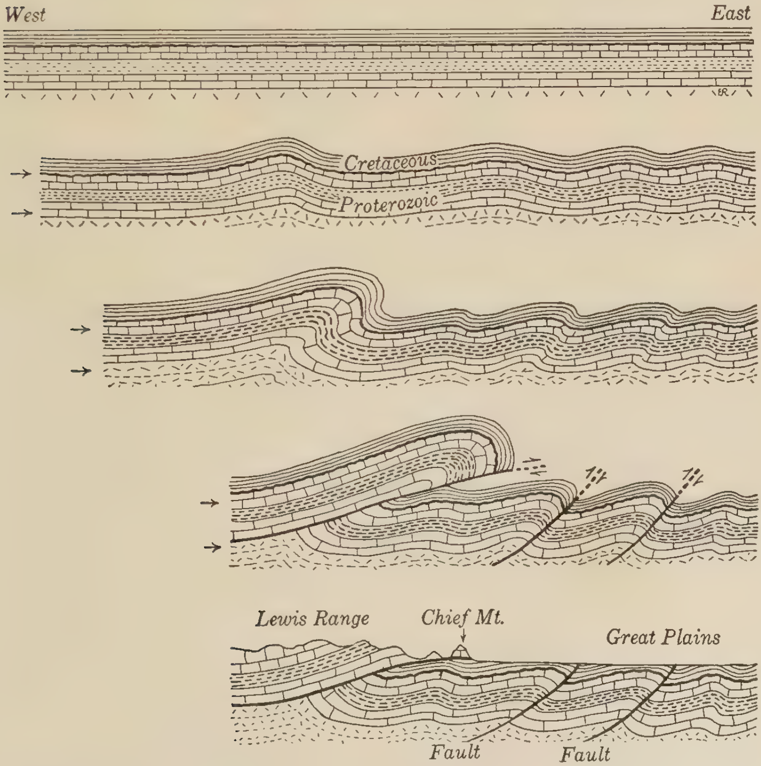

FIG. 144. Diagrams showing the successive stages in the history of the Lewis thrust fault in Glacier National Park. (Modified from Campbell. Courtesy of the United States Geological Survey)

faults with great heave in many areas. Thus the rocks which form some of the mountains in Glacier National Park have been pushed to the east as much as eight miles and probably more. In the process older rocks were thrust on top of younger rocks, and stand in this reversed position today (Fig. 144).

General characteristics of faults. Movement on fault surfaces may be horizontal, vertical, oblique, or rotational. In many faults vertical, horizontal, and oblique displacement took place simultaneously. In *rotary faults* movement may have been upward in one place, downward in another, and apparently lacking in another (Fig. 145). We have seen how displacement in stratified formations may give the appearance of either a normal fault or a reverse fault with a high vertical component of movement where movement had been largely or entirely horizontal (Fig. 137). The San Francisco earthquake of 1906 was caused by the horizontal movement along a fault plane. In imagining fault movements of any kind it is important to remember that the rocks of the earth's crust are three-dimensional bodies, and that any displacement within them is apt to affect three dimensions also.

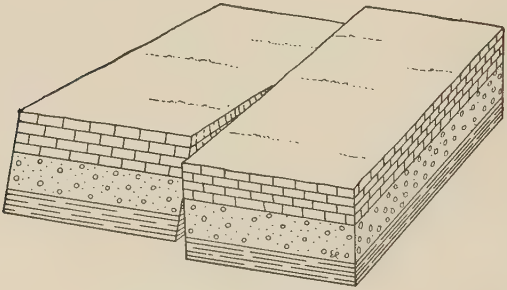

FIG. 145. A rotary fault

Not all fault planes are straight and smooth as the term *plane* implies. Some faults are displacements along a zigzag fracture, others branch, and still others curve. In some cases faulting is distributed along a series of more or less parallel planes. This process is called *distributive faulting* (Fig. 146). Ordinarily the rocky material forming the walls of a fault fracture is either grooved and rubbed smooth, or so broken that the fracture is filled with broken rock débris. Smooth, striated, or grooved fault surfaces are called *slickensides*. If the angular, powdery bits of rock produced in some faults are later cemented, the resulting rock is called a *fault breccia* (Fig. 147). Valuable ore-bearing solutions find the brecciated zone of faulted rock an easy avenue of approach to the surface; hence it is not uncommon to find breccias of this type well impregnated with copper, lead, silver, and gold-bearing minerals.

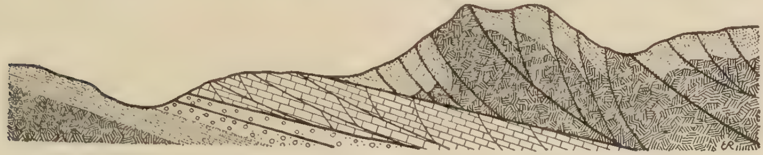

FIG. 146. Distributive faulting in the Scottish Highlands

Faults which saw displacement at steep angles may be marked on the surface by cliffs made from the up-throw sides. Such cliffs are called *fault scarps* (Fig. 93). In faults attending recent earthquakes such scarps can still be seen. Erosion works to obliterate the steep faces of fault scarps, so that in many cases normal faults having a displacement of several thousand feet cannot be detected by anything in the surface topography. A few great fault scarps of later geological time can still be recognized. Such a scarp is the west face of the Mission Range in western Montana, which rises abruptly to the extent of about a mile above the valley below.

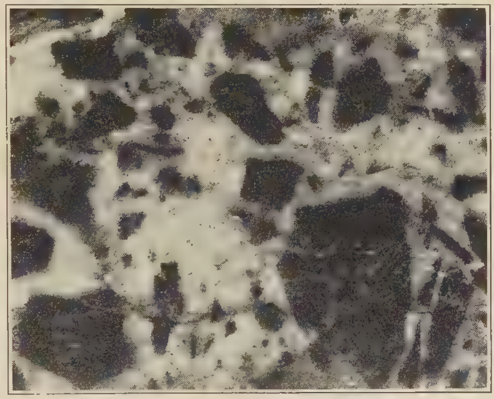

FIG. 147. A fault breccia

Origin of faults. Like joints, faults are the result of stretching (tension), twisting (torsion), or squeezing (compression) in the outer crust of the earth. In general, normal faults are the result of stretching and twisting, and reverse faults are the result of squeezing. Faults are genetically related to folds; in many cases the causative stresses are the same in both. These stresses are the result of earth shrinkage, and have been treated in Chapter IV.

Folds. Bedded rocks, whether sedimentary deposits or igneous lava flows, normally occupy horizontal or nearly horizontal positions. Earth movements, however, have caused such formations to buckle and wrinkle, so that the beds lie at various angles of inclination. Massive igneous rocks are likewise known to fold, but the folds are not readily seen or mapped. The inclination is known as the *dip* of the formation, and is the angle made by a tilted stratum with the horizontal plane. The direction of a horizontal line on the surface of a dipping stratum is called the *strike*. The strike is always perpendicular to the dip (Fig. 148). Enough has already been said to show that rocks in the field are seldom found in their original positions. A large part of the work of the geologist in a new region consists of mapping all available surface exposures of rock and determining their inclination by measurements of dips and their direction of trend by measurements of strikes; finally, by putting these pieces of information together, he gets the beginning of a coherent understanding of

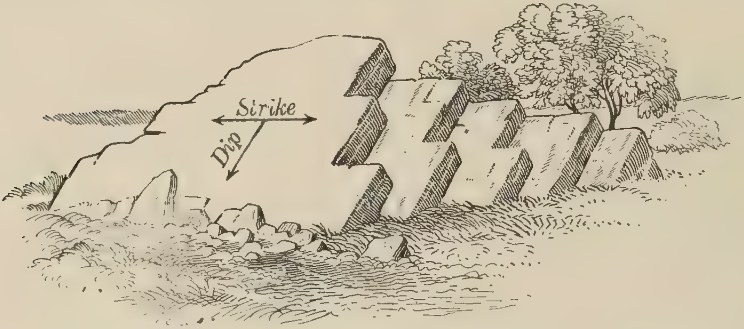

FIG. 148. Diagram illustrating the dip and strike of a formation

the structural relationships of the area as a whole. We have already studied the way in which faulting dislocates rock structures. Perhaps even more significant than faulting in this regard is the process known as folding. When the earth's outer crust is shortened by contraction, many rocks yield to the stresses by faulting, many others which are more deeply buried give way to the compressive forces in wrinkles, similar to the wrinkles developed in the sleeve of an overcoat when the wearer bends his arm. Such wrinkles in the bedded rocks of the earth's crust are called *folds.*

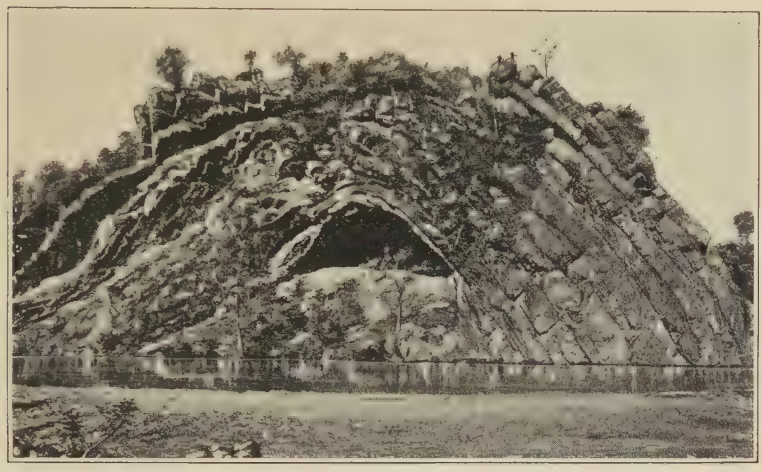

FIG. 149. An anticline in Maryland. (Courtesy of the United States Geological Survey)

Classification of folds. Like the waves produced by wind on the surface of water, rock folds can be divided into those which are convex and those which are concave. When strata are arched, the upwarped fold is called an *anticline* (Fig. 149). Between two anticlines, as between the crests of two waves, a troughlike area of depression ordinarily exists. The downwarped fold in rocks is known as a *syncline* (Fig. 150). Such wrinkles are often greatly modified by erosion, so that in some cases the anticline lies in a valley and the syncline lies under a hill. Present topography, however, is an afterthought in geological history, and the geologist must go deeper for the true significance of earth structures.

The crest of anticlines, known as the *axis*, may be but a few feet long or it may be several miles long. From the axis all beds dip away on both sides, or *limbs*. The axis may be inclined to the horizontal in an angle designated as the *plunge*. Synclines, on the other hand, have their axes along the bottom of the trough, and the limbs dip toward the axis rather than away from it. Like anticlines, synclines may plunge with reference to the horizontal (Figs. 151, 152). Folds may be of various styles. In some cases strata are bent by a single sharp flexure known as a *monocline* (Fig. 153). Rocks may be tightly folded or loosely folded. When the flanks of a fold are not in contact with each other, the fold is said to be *open* (Fig. 154). If the

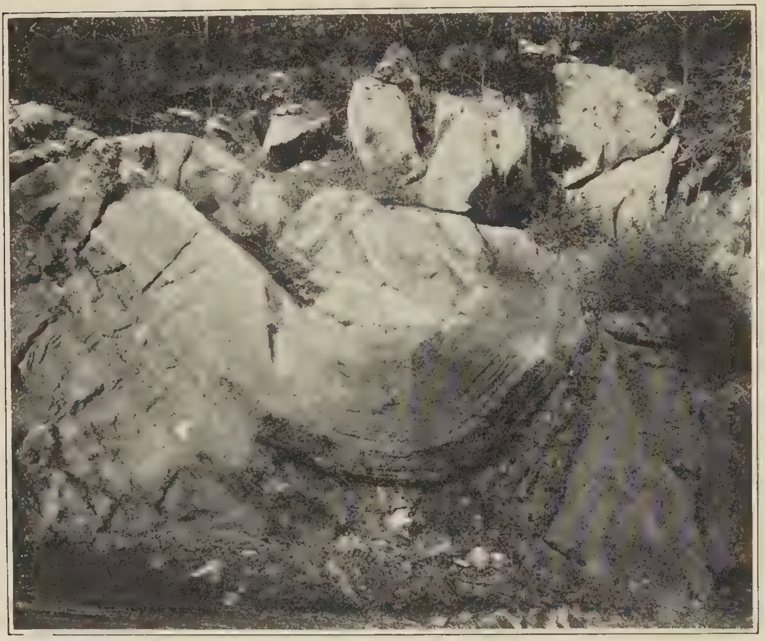

FIG. 150. A syncline in Tennessee. (Courtesy of the United States Geological Survey)

compression had been sufficient to bring the flanks together, the fold is said to be *closed* (Fig. 155). If several anticlines and synclines have been very tightly compressed so that the strata in their limbs are parallel or nearly so, the folds are called *isoclinal* (Fig. 156). Although folds may be *symmetrical* on both sides of an imagined plane passed through the axis and the center, most folds tend to have one limb longer and steeper than the other. Such inequalities produce *asymmetrical folds.* As the axial planes in folds approach the horizontal, the folds are said to be *overturned* (Fig. 158); when this plane is so nearly flat that the fold seems to be lying on one limb, the term *recumbent* is applied (Fig. 159). In some places, notably the Alps, pressure has been so great that

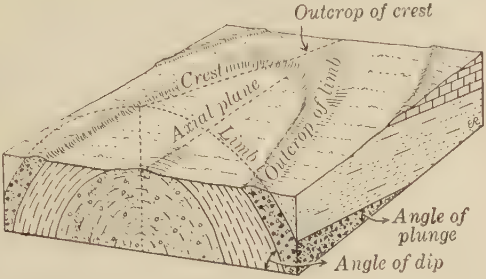

FIG. 151. Block diagram of an anticline showing parts

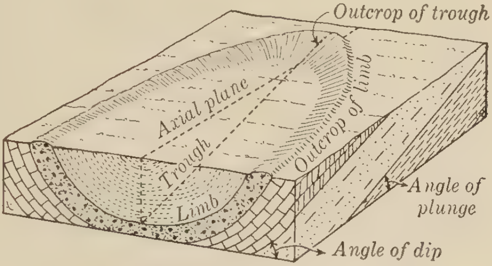

FIG. 152. Block diagram of a syncline showing parts

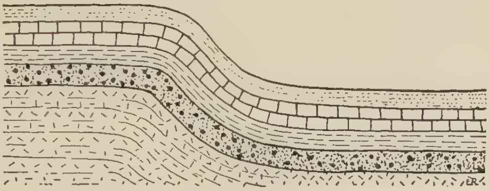

FIG. 153. A monocline

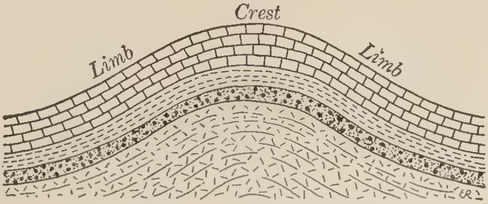

FIG. 154. An open anticline

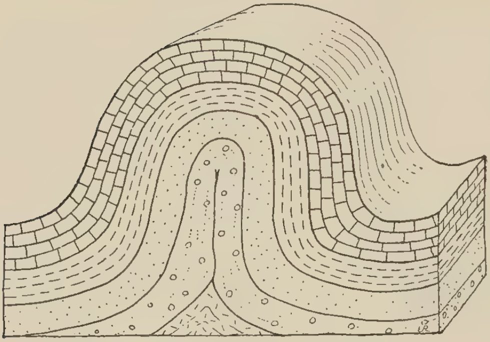

FIG. 155. A closed anticline

the sides of the folds have been squeezed close together so that the axial region flares like a fan; such structures are known as *fan folds* (Fig. 160). In mountainous regions where several folds occur, each individual fold, whether anticline or syncline, may be but an element on the flanks of a larger structure. If this structure is arched, it is called an *anticlinorium* (Fig. 161); if it is troughlike, a *synclinorium* (Fig. 162). If strata have been broadly flexed over several square miles, so as to form important architectural features in the earth as a whole, the terms *geanticline* and *geosyncline* are used. The city of Cincinnati is situated near the crest of a geanticline, and the Rocky and Appalachian Mountains are located in what were once geosynclinal troughs of great proportions.

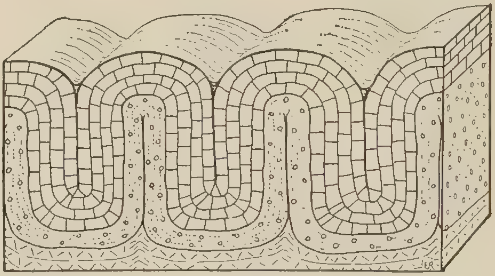

FIG. 156. Isoclinal folds

Origin of folds. We have seen that faults are the result of tension as well as of compression. Folds, on the contrary, are almost entirely due to the shortening of the formations of the earth's crust by the compression engen-

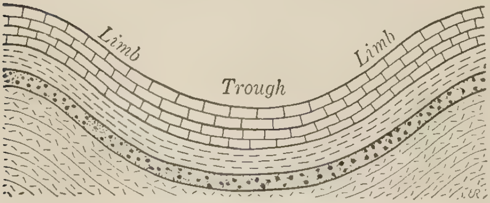

FIG. 157. Symmetrical syncline

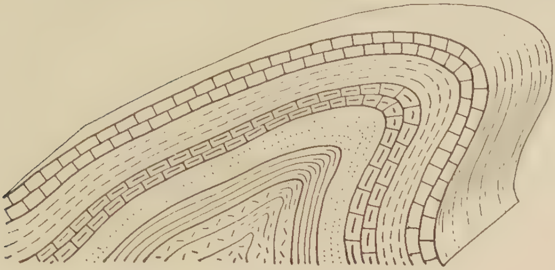

FIG. 158. Overturned anticline

dered in shrinking. Faults and folds are blood relatives and are often found together. If the pressure capable of producing an overturned fold is increased, it may slice the fold near its axis and produce a thrust fault (Fig. 163). The stresses resulting in the dislocation and folding of rocks are often similar and are best displayed in the architectural features of mountain ranges.

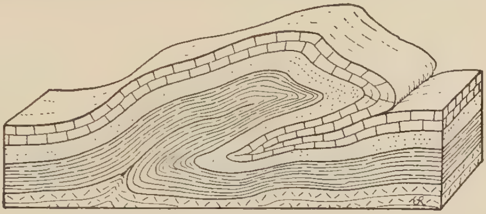

FIG. 159. Recumbent anticline

Structures of mountains. *Non-deformed mountains.* Not all mountains are found in deformed belts of the earth's crust. Erosion sometimes cuts into flat sedimentary beds and undeformed igneous rocks, so that a mountainous topography is produced. Such mountains are said to be *residual*; in most cases they are the remnants of plateaus which have been deeply dissected by river erosion (Fig. 164). The great Colorado Plateau has been so carved, and the flat-topped mountains found there are the result of wind and river sculpturing in horizontal sedimentary beds and lava flows. Some mountains are clearly due to the accumulation of

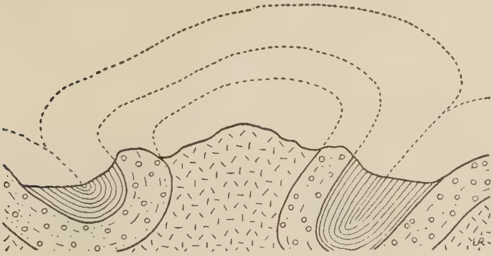

FIG. 160. Fan fold

volcanic materials and are known as *mountains of accumulation.* Fuji in Japan and the magnificent volcanic cones along the Pacific coast of North America, as well as others in various parts of the world, come under this classification.

Faulted mountains. The greater mountain ranges of the world are composed of rocks which have suffered deformation and uplift. In some places great blocks of the earth's crust have been raised along normal faults to produce the so-called *block mountains.* The ranges in the Great Basin between the Rockies and the Sierra Nevada are thought to have been carved out of such great faulted blocks. Block mountains often are steep on the side of maximum displacement and gentle on the other. Between ranges of block mountains sunken troughs occur in some areas. These are poorly drained and are often characterized by the presence of lakes. The Sierra Nevada of eastern California offers one of the best examples of block mountains. They were carved by erosion from a huge block of the earth's crust which was uplifted

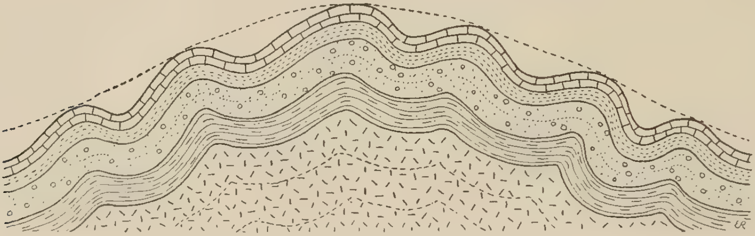

FIG. 161. An anticlinorium

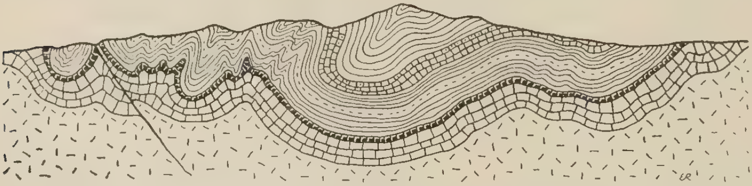

FIG. 162. A synclinorium, Mt. Greylock, Massachusetts. (Modified from T. N. Dale. Courtesy of the United States Geological Survey)

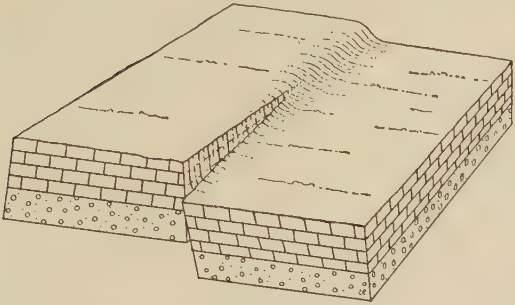

FIG. 163. Diagram illustrating the close relationship of faults and folds

A fault grading horizontally into a monocline. (See also Fig. 145)

rather recently in geological history and is probably still rising. The steep eastern front still exhibits the fault scarp along which the movement took place. This scarp rises sharply from five thousand to fourteen thousand feet above the valleys at its base. Block mountains seem to be the result of vertical uplift rather than of lateral compression, and for this reason are not typical.

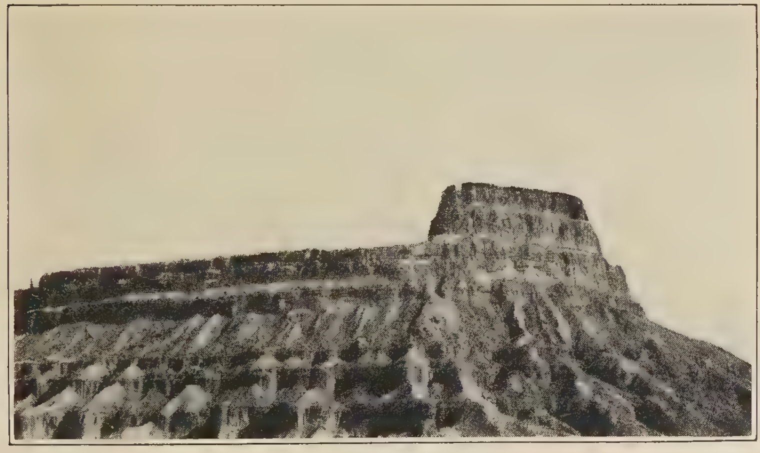

FIG. 164. A residual mountain in Utah. (Photograph by D. J. Fisher. Courtesy of the United States Geological Survey)

Such an upland remnant is known as a *butte* if the summit area is small and a *mesa* if great

By far the greatest number of mountains are the result of crustal shortening, although it is probable that most mountains of this type owe their present height largely to vertical uplift.

Thrust faulting is perhaps the most common structural feature in mountains derived from the compressed sediments of great geosynclinal basins. The Highlands of Scotland are the best illustration of how a segment of the earth's crust may be shortened and mountains be built by repeated overthrusting (Fig. 146). The Alps, the Himalayas, the southern Appalachians, and the northern Rockies show crustal shortening by thrust faulting on a large scale.

Folded mountains. Folding ordinarily attends faulting in mountains produced by compression. Some mountains are the result of igneous intrusion. In the Henry Mountains of Utah the sedimentary rocks of the region were domed by the injection of laccolithic masses between the beds. Mountains produced in this fashion, called *laccolith mountains,* are known in several localities in western North America (Fig. 165). Other mountains — the Black Hills of South Dakota and the Uinta Mountains of Utah, for example — were carved by erosion from great domelike anticlines, which were produced apparently by compression from the sides and without the aid of igneous injection and pressure from below.

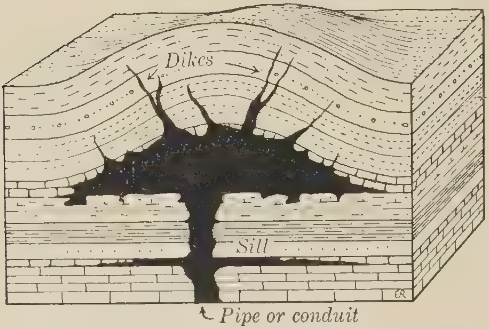

FIG. 165. Diagram of a laccolith, showing the dome formed in the overlying rocks. (Modified from Gilbert)

Mountains show all kinds of folding, from the simple domed types to the intensely crumpled forms best displayed in the Alps (Fig. 166). Some mountains are carved out of a gently undulating series of anticlines and synclines. When erosion attacks such structures, the synclines are ordinarily more resistant than the anticlines because the rocks in synclines suffer more compression and are therefore stronger than those in anticlines, where a certain amount of tension exists. As a result the anticlines may be worn down into valleys, and the synclines may remain, greatly modified, as mountains. Such *synclinal mountains* are well exemplified in the Appalachian region. On the other hand, the Jura Mountains in Switzerland are sculptured in gently folded strata, with the anticlines forming the peaks and the synclines forming the valleys (Fig. 167).

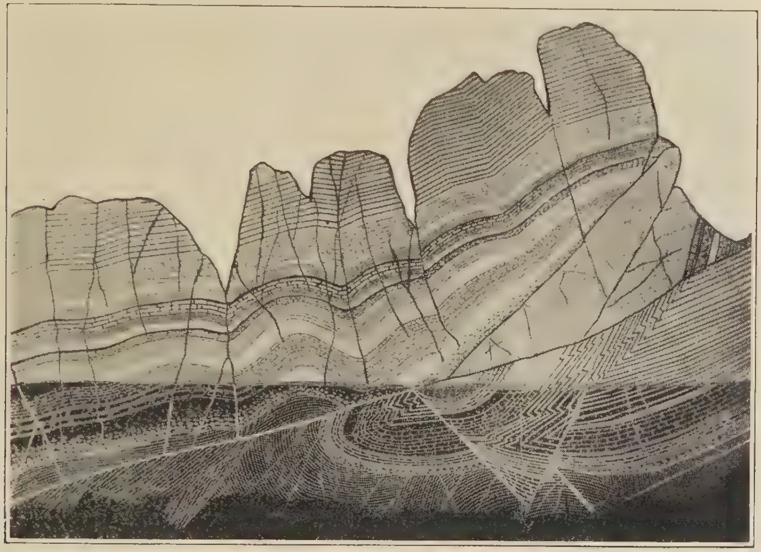

FIG. 166. Structure of the Ardennes, showing the complicated faulting and folding typical of the Alps. (After Cornet and Briart)

Erosion has removed all but the darker lower part

In more intensely folded mountain structures faulting is likewise involved, so that the effect of uplift and deformation may be exceedingly complicated. In many folded and faulted mountain ranges the process of deformation and uplift was repeated at intervals through a great length of time, causing further structural complication. Erosion, which is quickened by earth movements, greatly alters the appearance of mountain structures, in some cases so effectively that the architectural relationships can be deciphered only with difficulty.

Origin of mountain structures. We have already seen that the old theory of earth shrinkage is the best so far advanced to explain the most prevalent type of mountains, those formed from the crumpling of sediments in geosynclinal basins. Nearly all mountain ranges of this kind have cores of igneous materials, which indicate that at the time the earth yielded to the stresses developed in its crust by internal cooling, great outpourings of magma accompanied the folding of the rocks in the weakened areas. Such transfer of material from the interior of the earth to the exterior must have materially aided the cooling process in causing shrinking and buckling of the rocks on the surface.

Less satisfactory is the explanation of the mechanics of earth movements which result in mountains that appear to have been uplifted without crumpling and by vertical rather than lateral pressures. Block mountains are of this type, as are the great plateaus of the world. The frigid desert of Tibet stands about three miles above sea level, and its more or less level expanse stands higher than most mountain ranges. The Colorado Plateau stands at an elevation of over two miles above the sea. Where such plateaus have been deeply dissected by erosion they are as striking elements in the scenery of continents as are most mountain ranges. The rocks underlying these high lands are in many cases of marine origin. The problem of how they were lifted from sea level to the present height, *with little or no folding,* is one of the unsolved problems in earth science. The theory of isostasy, as we have seen, advances an explanation of such apparently vertically elevated land masses. Time, and the new knowledge that it will bring, can alone tell whether this or some other explanation is true.

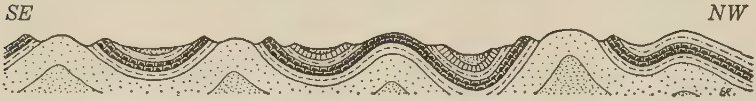

FIG. 167. Anticlinal mountains, Jura Range, Switzerland

CHAPTER VI

GEOLOGICAL TIME AND THE EVOLUTION OF THE CONTINENTS

HOW OLD IS THE EARTH?

The earliest attempts to estimate the age of the earth in terms that can be grasped by the human mind took the form of vague guesses, which have no value today. Not until the nineteenth century, when sufficient facts concerning the earth's history had accumulated, did any calculations of scientific value make their appearance. These and later calculations assign such a variety of ages to the earth that it is difficult to believe any of them more than remotely suggestive of the exact age of the earth. Great difficulties beset the daring investigator who attempts to estimate in years the vast eras of time which have slipped by since the globe had grown large enough to attract an atmosphere. Before this time the planet may be thought to have been in the pre-geological stages of its development; and since such geological processes as depend on the atmosphere did not exist at that time, the geologist has no basis for the measurement of the duration of this inconceivably remote period.

From the time when erosion set in to destroy the earth's surface, when rivers began to dissect the lands, and great piles of sedimentary débris accumulated in the depressions, records of successive stages in earth history were recorded in the rocks. Unfortunately these records are not continuous and are often obscured and read with great difficulty, so that only the order of magnitude of the time involved in earth history can be estimated. Great intervals of time when erosive agents were stripping the lands and depositing the débris in the ocean basins are registered by abrupt changes in the nature of succeeding formations, but not in a way that gives even a slight suggestion as to the time involved. The avenues of approach to the estimates of the age of the earth are briefly treated below. Let it be remembered that since there have been times in earth history which are unrecorded, and other times the duration of which is obscured in various ways that we shall presently consider, no estimate of the age of the earth, based on geological phenomena, is sufficiently long. The earth is certainly as old as all available data of a positive kind lead one to believe it is, and very likely much older.

Evidence from erosion. We know that rivers are daily carrying to the seas rocky material worn from the lands. Compared with the ordinary measurements of mankind, the yearly amount of material deposited in the ocean by a single great river seems great (the Nile dumps over fifty million tons of rock débris on its delta every year), but the rate at which rivers affect the appearance of the lands seems insignificant. We may dwell throughout our lives on the bank of a river and see no apparent widening of the valley. Yet rivers do widen their valleys, but at a tremendously low rate compared with the brief span of a human lifetime. At St. Louis the bluffs of the Mississippi River stand about twenty miles apart. At one time the Mississippi was a young river, and its valley walls were close together. At some future time, if conditions remain the same as they are today, the bluffs flanking the Mississippi will be appreciably farther apart. How long does it take a river to proceed from youth to maturity and from maturity to old age? How long does it take to reduce a land to essential flatness? Nobody knows, but estimates have been made of the present rates of erosion in some of the great rivers of the world. At the present rate the widening of the Mississippi Valley at St. Louis must have taken at least one million years. Peneplanation, the reduction of great land areas to near flatness by river wear, must have required much longer, perhaps tens of millions of years. Since the rocks of the earth's crust give good evidence of repeated peneplanation during the progress of geological history, the age of the earth based on present estimates of river erosion would be near, although probably in excess of, a hundred million years.

Evidence from deposition. More than sixty-five miles of stratified rocks have been laid down in the course of the earth's evolution. If we knew the average rate of deposition, the length of time required to amass such a thickness of sediments could be computed. Unfortunately the rate of deposition even at the present time is variable, not only from year to year in the same area but in different areas at the same time. Lands stand higher now than they have stood throughout all of later geological time. Erosion, therefore, is piling up sediments at a greater rate now than during much of the past. It has been estimated that at the rate the Nile is now building up its delta, the sedimentary rocks of the earth would take at least twelve million years to accumulate. It can be seen that if allowance is made for a slower rate of deposition in the past and for the epochs when great areas were peneplained and rivers delivering little or no sediment to the oceans, the earth must be very old. While an accurate estimate is impossible because of the variability of the rate of deposition, a conservative guess from the evidence of sedimentary rocks would be that the earth is at least a hundred million years old.

Evidence from mountains. There is an abundance of evidence to prove that mountains are built very slowly. Most convincing, perhaps, are the antecedent rivers which hold their courses athwart a region of uplift and cut into the mountains as fast as they rise. We know that rivers degrade their channels very slowly; hence we infer that mountains cut by antecedent streams must have risen equally slowly. Yet in the history of the earth lofty mountains have been repeatedly lifted and worn to flatness, leaving nothing but their worn stumps and great piles of sedimentary débris to commemorate their former eminence. Although the time involved cannot be determined in years, it must have been great — so great that the human imagination cannot fully grasp its significance.

Evidence from the salt in sea water. It is believed that in the beginning the oceans were fresh, and that the sodium salt now found in all of them was dissolved from the rocks of the lithosphere. For a long time geologists have been interested in estimating the age of the ocean on the basis of the rate at which sodium salt (common salt) is supplied to the sea by rivers. This rate seems to be fairly constant; and since a nearly exact estimate of the total amount of sodium now in the sea can be made, by assuming that the rate of supply was as constant in the past as it is now, an estimate of the age of the ocean can be made. The fallacy in such an estimate is the presumption that salt has always been carried to the sea at the present rate. The changing picture of the continents which geological history gives, with variation in the amount of material eroded from the land and deposited in the sea from age to age, would indicate the contrary. Nevertheless the age of the oceans computed from the sodium content, while not exact, gives at any rate the order of magnitude of the time involved in their history.

As early as 1715 Edmund Halley suggested the possibility of ascertaining the age of the oceans in this way, but not until 1899 had sufficient data accumulated to make such an estimate possible. In that year the Irish physicist Joly, using the figures at hand for the average yearly amount of sodium in river water and the estimated mass of sodium in the sea, by simply dividing the second by the first, calculated that the oceans were 97,600,000 years old. Other estimates have been made, but all give nearly 100,000,000 years as the age of the sea. Certain amounts of sodium are received by the sea through other agencies than rivers, and cannot be entered in the equation; other sodium is lifted by the spray and borne landward by the wind from the ocean, to return to the sea again as *cyclic sodium.* From the nature of these phenomena no satisfactory correction can be made in the equation. Furthermore, any estimate of this type must forever be of a very general nature, since no one can ever know the rate by which rivers of the past have added to the sodium in the sea. From evidence of an entirely different nature it would seem that the oceans of the earth are far older than these estimates imply.

Evidence from plants and animals. The rocks carry a long and complicated record of the organisms that peopled the earth at successive stages in its history. The history of life is treated in Chapter VII; but, without anticipating, it can be said here that the changes which living creatures experienced during their long history took place with excessive slowness. The plants and animals of today are not noticeably different from those described in the earliest human documents. Five, ten, or fifteen thousand years may pass without effecting any appreciable change in the general aspect of the world's life. Yet changes of a striking order have taken place, as we shall see. The oldest preserved records of life on earth are vastly different from those of middle geological time, and these, in turn, differ widely from the organisms of the present day. Whole dynasties of creatures rose to dominate the seas and lands of the past, only to fall into the oblivion of extinction and to be succeeded by other dynasties. The very oldest known fossil plants and animals show by advanced and degenerate structures that a long ancestry, entirely unrevealed, must have gone before. All these facts prove that the earth is very old, — so old that the brief flash of a year or a century loses all meaning.

Evidence from radioactivity. Experiments by physicists and chemists have shown that a few of the elements in nature, such as thorium and uranium, are unstable and are constantly breaking down into different things. Such elements are composed of heavy atoms, and when they break down they always give rise to elements of lighter atomic weights. For example, uranium passes into radium after many successive stages, giving rise to helium and ultimately to lead, which are stable products. The speed with which these unstable substances pass from one stage to another in their decay causes rays of various sorts to be emitted, and because of these rays the substances possessing them are said to be radioactive. The rate of this transformation cannot be altered, and is accurately known by experiment.

The age of a given rock or mineral can be estimated by measuring the amounts of uranium and helium it contains. Since the length of time required to generate the helium (one of the end products of the decay of uranium) is known, sufficient data can be had to estimate the age of the specimen in hand. Thus Strutt found a piece of rock from Ceylon to be two hundred and eighty million years old, Rutherford found other rocks to be five hundred million years old, and still other investigators have calculated the age of other rocks as high as one billion six hundred million years. Other methods of studying radioactive minerals and rocks lead to various results, but in general the estimates of the age of the earth based on the "radioactive clock" are from ten to fifty times as high as those based on geological evidence. This discrepancy is partly due to the fact that the geological methods cannot measure the breaks or missing intervals in the earth's history and undoubtedly give rise to underestimation. On the other hand, the variance in ages computed for rocks by different investigators of radioactive substances makes it seem likely that the methods of calculating the age of rocks in this way might be improved. Such discrepancies are as yet unexplained, and until they are explained the great age of the earth suggested by experiments on radioactive substances must be considered questionable.

THE STORY TOLD BY ROCKS

Erosion intervals. Every rock in the earth's crust contains an autobiography for those who can read it. By interpreting and compiling the life stories of rocks, the history of the earth itself has been learned. Since most of the surface of the continental blocks is occupied by sedimentary rocks, it is from a study of this type of deposit that the earth's history has been read. Where strata have accumulated in unbroken succession, the particular region now occupied by the undisturbed sediments is believed to have been essentially free from earth movements during the time of deposition. Such strata as lie in unbroken succession are said to be *conformable*. Where a series of conformable beds have been elevated, attacked by erosion, and a second series of strata deposited upon the first at a later time, the two series are said to be *unconformable.* The erosion surface between the two series of strata is called an *unconformity.* Unconformities are of two main types: (1) if the lower series of strata were uptilted and beveled by erosion so that the upper series rest on the edges of the first, the unconformity is called *angular*; (2) if no discordance in dip exists between the beds below and above the erosion surface, the break is called a *disconformity* (Fig. 168). Disconformities in the sedimentary history of the earth can often be distinguished in the rocks by the presence of coarse sandstones or conglomerates laid down on the ancient erosion surface. Such coarse sediments are normally the first to be deposited when the sea encroaches on an old land surface. Where basal beds of this character are absent, the break may be difficult to detect because of the conformable relationship of the strata above and below the erosion surface. This surface, however, may be undulatory because of the differential attack by erosive agents.

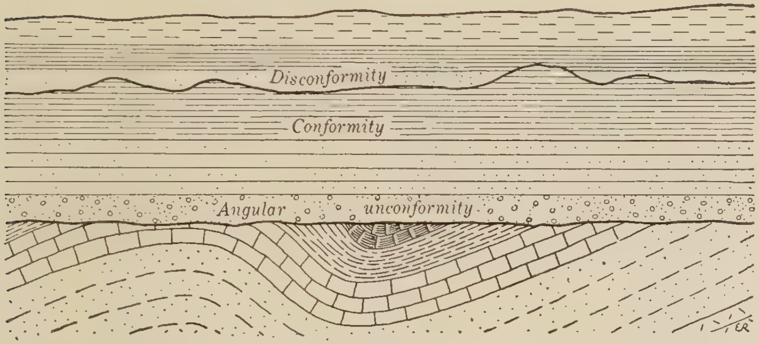

FIG. 168. Diagram illustrating conformity, angular unconformity, and disconformity

Unconformities are important for the geological history they depict. They reveal (1) a time of quiet deposition during which the lower series of strata were laid down on the sea bottom; (2) the consolidation of these sediments and their elevation, which may have left them in their original horizontal position or may have tilted or folded them; (3) a long time when erosion attacked the new land; (4) depression of the new land to its original condition as part of the sea bottom; (5) deposition of more sediments upon what is now an old land surface; (6) reëlevation, which again changes the sea into land; (7) and finally, the present epoch of erosion. Unconformities may likewise exist between igneous and sedimentary rocks and between metamorphic and sedimentary rocks, and each discloses a story of events in the history of the earth.

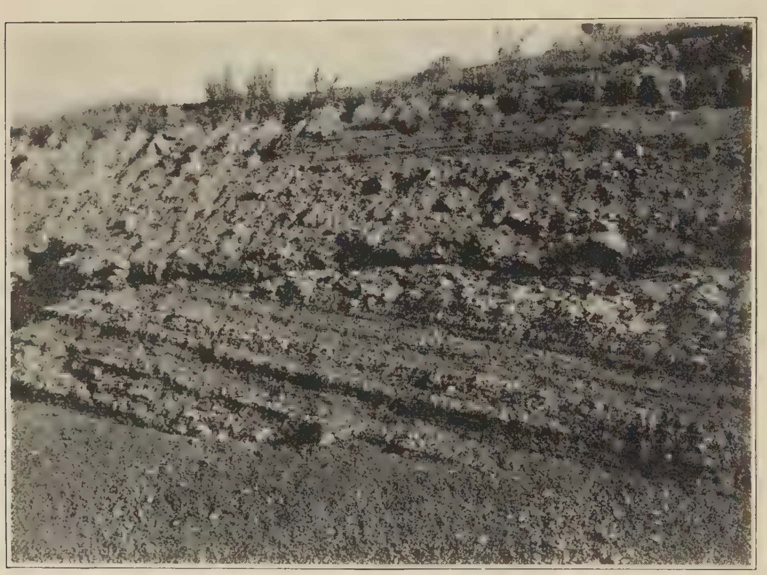

FIG. 169. Angular unconformity, Oregon

Character of deposits. While little can be known about the events which transpired during the time when an area was above the sea and suffering denudation, a great deal can be learned from the nature of the sediments laid down upon it when it was submerged. Since shallow seas have again and again invaded the continental regions and left behind a blanket of sediments, most of the direct knowledge of the earth's history is based upon a study of these deposits. Entombed fossils and the presence of mud cracks, ripple marks, and similar phenomena show that most sedimentary rocks originated near shore under very shallow water. Most sedimentary formations are evenly bedded, proving that waves and currents were not sufficiently powerful to disturb a regular deposition. Some are coarse-grained and resemble beach deposits on present-day seacoasts; others are finer-grained and suggest an origin in deeper water farther from shore. Some sedimentary rocks are dark, others are light; both tell the story of their descent. Some show that they were deposited on land under arid conditions; others were formed in moist regions. The distribution of marine deposits throws light on the distribution of the seas in which they were laid down.

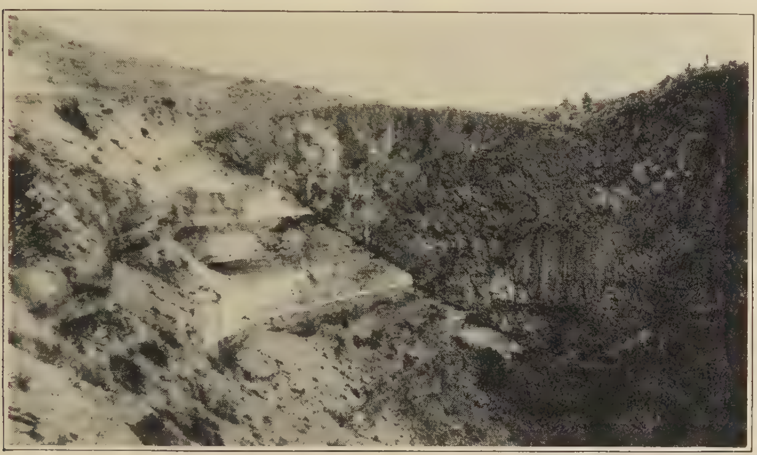

FIG. 170. A study in earth history. (Photograph by J. P. Buwalda)

On the left are flat-lying, fossil-bearing sediments deposited in the waters of an ancient lake. After deposition the sediments were cemented into rock and uplifted. Streams then began to furrow the new land with valleys which at a later date were filled with lava. The picture shows such a lava-choked valley, which erosion has again opened to view. Note the diagonal contact between the lavas to the right and the sedimentary beds on the left

How fossils are used. By the aid of fossil plants and animals entombed in the rocks a great deal has been learned about the physical conditions of the earth at the time of their existence.

Fossils tell whether the rocks were formed on land or under the sea and also something of the characteristics of these lands and seas. If the lands were dry or moist or cold or warm, the fossils preserve a record of it. If the seas were cold, certain types of animals, such as corals, could not live and are not preserved as fossils; if the seas were warm, an abundance of shells of warm-water creatures remain to testify to the fact. If the sea in which the sedimentary rocks were deposited was deep or shallow, fossil shells of animals with deep-water or shallow-water habits are preserved. These and many other facts are disclosed by fossils, which, together with the knowledge gained by a study of the nature of the rocks, furnish the geologist with data by which he unravels the history of the past.

The divisions of geological time. All rocks in the accessible parts of the earth's crust are grouped according to their time relationships. The larger divisions of time involved in the earth's history and the corresponding rocks which give a record of the events during each division are as follows:

Time	Rocks
Era	Group
Period	System
Epoch	Series
Age	Formation

Thus an era of time is represented by a *group* of rocks, and these in turn include several *periods* of time and *systems* of rocks. Periods and systems are divided into *epochs* and *series*, which in turn are composed of *ages* and *formations* respectively.

It is clear that if the rocks of the earth's crust have not been disturbed, the older rocks will be found underneath the younger. In areas whose underlying formations have been disturbed by faulting or overturned folding, the natural succession of formations may be so greatly obscured that it is necessary to determine the age of the rocks by other methods than a study of their superposition. All rocks of the earth which are open to the study of the geologist belong to one of the following major divisions of geological time:

Eras	Periods	Epochs
Cenozoic	Quaternary	Recent Pleistocene
	Tertiary	Pliocene Miocene Oligocene Eocene
Mesozoic	Upper Cretaceous	
	Lower Cretaceous	
	Jurassic	
	Triassic	
Paleozoic	Permian	Carboniferous
	Pennsylvanian	
	Mississippian	
	Devonian	
	Silurian	
	Ordovician	
	Cambrian	
Proterozoic (Algonkian)		
Archeozoic (Archean)		
Pre-geologic		

The larger divisions or eras of geological time are marked by a general absence of great deformative movements of the earth's crust and by a more or less homogeneous assemblage of organisms. Each era is terminated by a period of widespread mountain-building and general uplift of the land followed by prolonged erosion. In this way each group of rocks representing an era of time is separated and sharply marked off from each similar group by an unconformity of world-wide distribution.

In like manner each period of time and system of rocks is bounded by breaks in the geological record, but these breaks are of less significance than those between eras of time and groups of rocks. Periods may be terminated by disturbances in the crust of the earth, but these are less widespread and less intense than those mountain-building movements which terminate eras. A period is normally characterized by a marked submergence of the continents under a shallow encroaching sea and by a marked emergence during which time most of the land is above water and suffering erosion. Thus systems of rocks may be separated by unconformities, but these are of less extent and represent shorter intervals of break in the geological record than those which separate groups of rocks.

In the same way epochs and ages are recorded as still smaller divisions of geological time, and their records in the rocks are preserved by minor breaks of but local importance.

THE PRE-GEOLOGICAL HISTORY OF THE EARTH

The earth's place in the universe. The fascinating picture that astronomy gives of the vast space surrounding the earth, with its myriad inhabitants of stars, planets, nebulæ, meteors, and comets, presents some of the greatest problems with which the human mind has attempted to cope. Because the earth is part of this picture, though but an inconceivably minute part, the geologist must turn to the heavens for an explanation of this planet's origin. Celestial bodies fall into two main groups (at least so far as the earth is concerned) known as *stars* and *planets*. The twinkling pin points of light to be seen in the sky on clear nights are but a small portion of the two or three billion stars estimated to exist. As earth dwellers we are interested primarily in one star, the sun. Circling around the sun are eight heavenly bodies called planets, dead stars or fragments of stars which shine by light reflected from the sun. This little colony, lost in the immensity of the universal cosmos, is the focal point of our attention, inasmuch as the earth is one of the coterie of planets attendant on the sun. With the earth are seven other planets, Mercury, Venus, Mars, Jupiter, Saturn, Uranus, and Neptune, all circling around the sun. This assemblage is called the *solar system*. There is evidence that other heavenly bodies outside the solar system are grouped in orderly arrangement.

The vastness of space beggars imagination. Some of the stars nearest the earth are several million millions of miles distant. The distances within the solar system, which we have characterized as a little colony in the known universe, are appalling. Thus the earth is nearly 100,000,000 miles from the sun, and Neptune is nearly 3,000,000,000 miles distant from the sun. A bullet shot across the orbit of this planet would consume about five hundred years in traveling from one side to another in a straight line. Mercury, the planet nearest the sun, is 36,000,000 miles away. Compared with the distance of the earth from the nearest star, Alpha Centauri, the solar system is a relatively compact group of heavenly bodies. Astronomical distances are so immense that they are measured by the time consumed by light in traveling from one point to another. Light, which travels at the rate of somewhat more than 186,200 miles a second, requires four years and three months to pass from the sun to Alpha Centauri. Sirius, the Dog Star, is over twice as far away, and its light requires about nine years to travel to the sun. The Cluster of Hercules is so distant that light emitted from it at the time of the birth of Christ will not reach the earth until after the year 34,000. The greatest distance within the solar system, that between the sun and the planet Neptune, is traversed by light in the relatively short period of about four hours and thirty minutes.

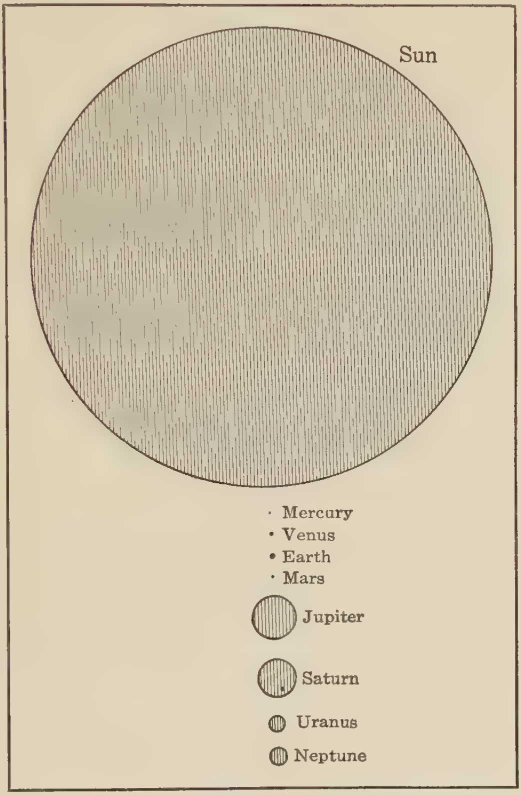

FIG. 171. Diagram illustrating the relative size of the sun and planets

The size of the sun, although small in comparison with some other celestial bodies, is likewise immense. The diameter of the sun is over 860,000 miles, 108 times that of the earth, and nearly 300 times that of the smallest planet, Mercury. Compared with its family of planets, the sun is overwhelmingly great; it contains almost 99.9 per cent of the mass of the entire solar system. In the remaining 0.1 per cent are included all the planets, with their moons, asteroids, and meteors, and all the comets under the control of the sun. Compared with some other stars, however, the sun appears of less importance. Thus, Antares, the brilliant star in the constellation of Scorpius, is over 280,000,000 miles in diameter, or over 325 times the diameter of our sun. The earth, which is the fourth smallest planet rotating about the sun, with a diameter of 7918 miles, is but an insignificant part of the solar system and a negligible quantity in the cosmos as a whole.

Early history of the earth planet. Much speculation on the origin of the solar system can be found in the literature of science. With the passage of time some of the laws which govern celestial bodies have been discovered, so that the more modern theories of the origin of the earth are not entirely speculative in their nature. The early notions of a solar system born of chaos can no longer be sustained, because the high organization not only of the solar system but of the entire cosmos today belies such a belief.

The theory of the earth's origin most widely accepted among scientific men today is the *planetesimal hypothesis* of Chamberlin. The following discussion presents but the briefest skeleton of this hypothesis, which leads very rapidly to astronomical, mathematical, physical, and chemical considerations far beyond the scope of this book. A brief treatment of the planetesimal hypothesis is introduced to give the student a general picture of the most plausible account of that part of earth history which is still shrouded in obscurity and about which nobody can yet speak with final authority.

In searching the heavens for a possible clue as to the original condition of the solar system, the eye of the observer is arrested by certain luminous, cloudy patches called *nebulæ*. Several hundreds of thousands of nebulæ are already known, all of which are very large. Certain of them have a spiral form and are called *spiral nebulæ*; over a hundred thousand such are now known (Fig. 172). The planetesimal hypothesis postulates the birth of a star such as our sun from the condensation of an irregular nebulous mass. It explains the formation of a spiral nebula by the close approach of a visiting star which exerts a tidal pull on the original star. We know that the materials near the surface of our sun are being shot far out into space with explosive violence and then drawn back by gravity. It is easy to conceive that under the attraction of a visiting star some of this material may be drawn out beyond the limit within which the original sun has power to pull it back again. The planetesimal hypothesis states that our ancestral sun was so disrupted by the close approach of a visiting star that ma-

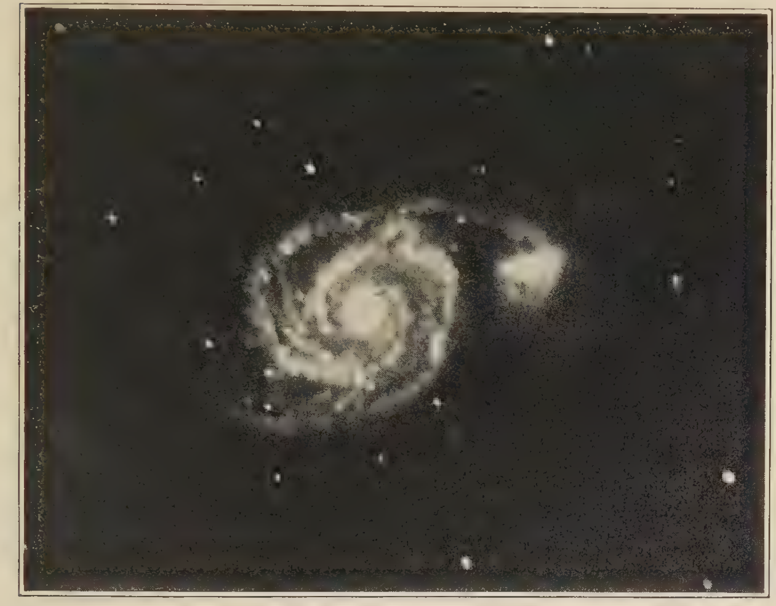

FIG. 172. A spiral nebula. (Courtesy of G. W. Ritchie and the Yerkes Observatory)

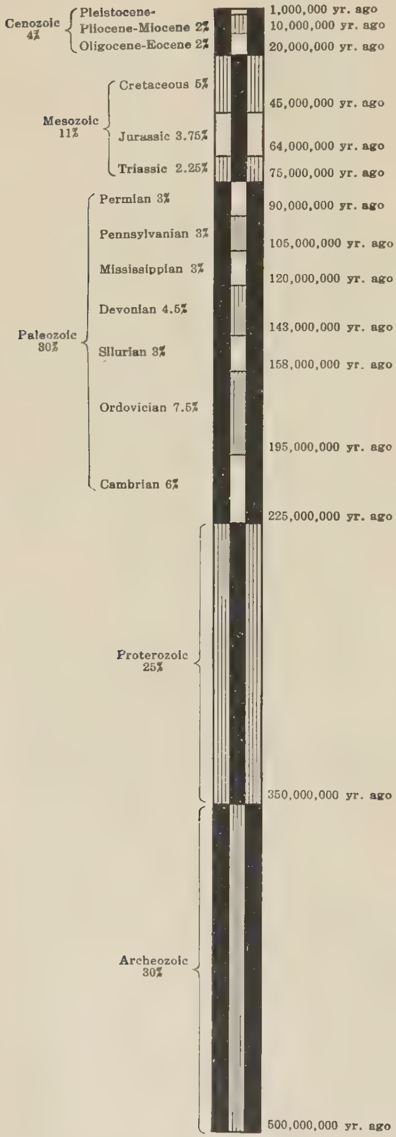

FIG. 173. A chart of geological time. (Duration of time divisions based on calculations by Charles Schuchert)

terial forced out on both sides assumed the shape of spiral arms under the sun's rotation, and in the intense cold of space (the so-called absolute zero, – 273° C.) the materials constituting the arms quickly changed from gas into liquid and solid substances, which took the form of spherical bodies of different sizes revolving about the sun.

Such a nebula differed in no way from similar ones now known to astronomers, with the exception of being much smaller. The condensation of material in the arms of a spiral nebula produces nuclei or knots of matter, small and large, with much fine material between. The particles of this finer material are called *planetesimals,* or little planets. The earth and the other planets in the solar system are thought to have been knots in the arms of a spiral nebula, with the sun at the center. With the passage of time the planet knots slowly cleared the space within their orbits of the planetesimal material by overtaking and gathering in the small particles. Thus the earth knot, which was solid from the beginning, slowly grew by gathering in all the scattered planetesimals whose orbits brought them within the influence of the larger body.

According to this hypothesis the earth was not large enough to attract gases until it had grown to at least one tenth of its present mass. Not until it had a diameter of forty-two hundred miles is it thought to have had an atmosphere comparable to the present one. When water vapor accumulated to such an extent that the atmosphere was saturated, some of it fell to the earth and settled in the depressions on the crust to begin the oceans. Some of the materials in the atmosphere may have been contributed by vulcanism, which must have begun at an early date in the growth of the earth knot. Life did not begin until after the birth of the atmosphere and the hydrosphere, although there is evidence to support the belief that bacteria could have existed on the earth long before suitable conditions for other living things had been evolved. With the passage of more time the planetesimal material was nearly all gathered in, the gradational processes of air and water began to modify the earth's surface, and its geological history began.

THE PRE-CAMBRIAN ERAS

A belief fast losing its popularity among scientific men postulates a stage in the cosmical history of the earth planet when that body was completely liquid. It was thought that by loss of heat the earth had gradually acquired a solid crust over a still liquid interior. Under such a hypothesis one might well expect to find among the oldest rocks some remnant of the earth's original crust. No such relic has ever been detected, and, what is more important, some of the very oldest rocks are of sedimentary origin. Sedimentary rocks show that at the time of their formation the earth had an atmosphere and was cool enough so that water could stand in the depressions of its surface without turning to steam. Beneath these oldest sedimentary rocks are volcanic tuffs which have clearly been reworked and stratified by water. If the earth had passed through a liquid condition and had developed a crust of solidification, it would seem likely that the oldest rocks available to study would be crystalline and igneous in nature. To find sedimentary rocks formed at a time when the earth was formerly supposed to have been too hot to support a hydrosphere strongly favors, in an indirect way at least, the "cold-earth" hypothesis of origin sketched above.

Archeozoic time. The earliest era in the geological history of our planet is represented by a highly complicated succession of rocks known as the Archeozoic ("primitive life") formations. Together these are known as the "basal complex": basal because they underlie all the later sedimentary rocks, and complex, because they are greatly folded, faulted, and metamorphosed, as a result not only of the deformative movements and vulcanism suffered during and directly following their formation but also of deformative movements and vulcanism affecting the earth's crust throughout all subsequent time to the present.

Rocks of this early date appear at the surface of the earth only where erosion has removed the later formations, or where uplift has raised and erosion bared these deep-lying formations in mountain regions. The surface distribution of Archeozoic rocks comprises about 20 per cent of the land area of the earth, which is rather more than we should expect. In North America a great territory in eastern and central Canada, from Lake Superior northeast to Hudson Bay and Labrador, known as the "Canadian Shield," is directly underlain by Archeozoic rocks. Smaller linear belts of outcrops occur in the Appalachian and Rocky mountains. In Europe these ancient rocks are widespread in Scandinavia, and outcrops of smaller dimensions are known farther south. Most of Brazil and central Africa, as well as large areas in China, India, and Australia, are likewise of Archeozoic age.

Although undoubted sedimentary rocks occur near the base of the Archeozoic in North America, they are notable exceptions among rocks of this age. Archeozoic rocks, wherever

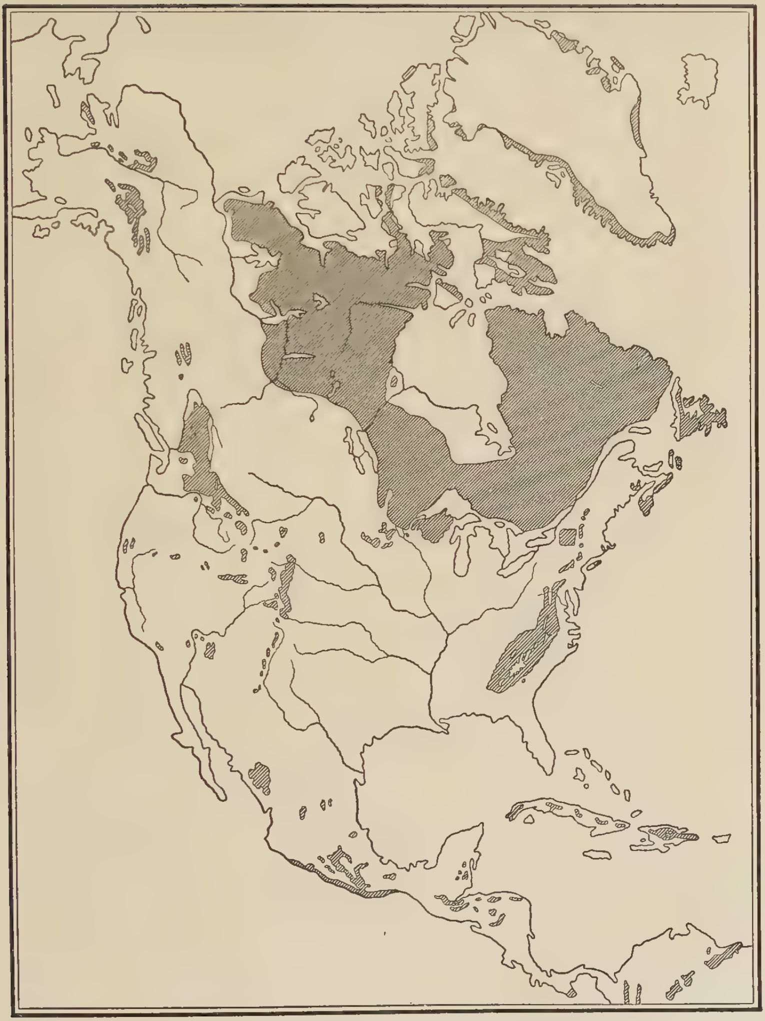

FIG. 174. Map showing the distribution of pre-Cambrian rocks in North America. (After Bailey Willis. Courtesy of the United States Geological Survey)

exposed, are preponderantly gneisses, schists, and granites. The old schists of the Canadian Shield appear to have been derived largely from lavas and tuffs through metamorphism induced by intense folding. In most cases the gneisses were derived by metamorphism from granite intrusions which repeatedly cut through the older sedimentary and volcanic rocks. The intensity of the folding, faulting, and vulcanism which everywhere characterize Archeozoic rocks makes it easy to distinguish them from younger formations, but so complicates the relationships within themselves that little progress has been made in the interpretation of Archeozoic history over any large area. In younger sedimentary formations contemporaneous strata in separated areas may be known by the similarity of fossil remains as well as by similarity in the superposition of the rocks, but in the Archeozoic, where fossils are almost entirely absent and deformation is extreme, contemporaneous formations can be known only by (1) comparison of the rocks from the standpoint of composition and general appearance, (2) the comparative degree of alteration in the rocks of separated areas, and (3) the age of certain great granite intrusions which are believed to cut earlier rocks of the same age over wide areas. Such a method is fraught with uncertainty, since rocks of the same age may vary in make-up and appearance from place to place, since rocks may be more intensely deformed in one area than contemporaneous rocks in another, and since the granites which appear similar and hence contemporaneous may really be similar but of different ages in different areas.

From the great but unknown thickness of Archeozoic rocks throughout the world it is generally believed that this time was of immense duration, possibly comparable to two or more geological eras. Some geologists believe Archeozoic time to have been of longer duration than all subsequent time to the present. For this great chapter in the earth's history only comparatively few events of broad significance are known with any degree of certainty. These events are briefly as follows:

1. *Keewatin time,* when the earliest known rock formations were made (in the Lake Superior region), is represented by a great thickness of metamorphosed volcanic tuffs, lavas, and breccias with occasional interbedded conglomerates, shales, and beds of iron ore of aqueous origin. These formations collectively are known as the Keewatin. At the same time or somewhat later great thicknesses of predominantly limestone rock accumulated farther east in the St. Lawrence valley. One estimate determines the thickness of these beds as approximately eighteen miles (94,000 feet), of which over half is limestone and dolomite. If this estimate is correct, the prodigious thickness of the so-called Grenville limestones exceeds the thickness of any other limestones in the crust of the earth.

2. *The Laurentian revolution,* when the Keewatin rocks were invaded and distorted by large granite batholiths, was one of the greatest periods of igneous intrusion in the history of the earth, if not the greatest of all.

3. *A long interval of uplift and erosion* during which time the Laurentian granites were uncovered and deeply dissected by running water. Such a revolution as the Laurentian, followed by erosion, came as a conclusion to every era in geological history, although the disturbance at the climax of the Archeozoic was marked by more igneous activity than were later disturbances of the same nature.

Proterozoic time. While the earliest events of Archeozoic time are buried in the unrecoverable beginnings of geological history, the next following era, the Proterozoic ("former life"), is recorded definitely in the rocks of the earth's crust. The long and widespread period of erosion that terminated the Archeozoic, and the consequent unconformity by which it is recorded, everywhere presents a sharp boundary line between the formations of this time and the later Proterozoic formations that overlie. No less profound a break is registered in the contrasted character of the Archeozoic and Proterozoic rocks. The Archeozoic formations are largely of igneous and metamorphic nature; the Proterozoic formations are mainly of sedimentary origin. In nearly all respects the Proterozoic rocks resemble those which were formed at later dates in the history of the earth, and bespeak essentially the same conditions which obtain on the earth today.

Much of the old land surface that suffered prolonged erosion at the close of the Archeozoic was invaded in Proterozoic time by seas in which were deposited a variety of sediments. These were later consolidated and uplifted, so that in many places they stand today as testimonials of Proterozoic events. Their distribution is much the same as that of the Archeozoic formations, upon which they were laid down. In North America they can be observed best in the Canadian Shield area of central and eastern Canada, in the Grand Canyon of Arizona, where over ten thousand feet of Proterozoic sediments have been exposed by the down-cutting of the river, and in western Montana and British Columbia, where the Rocky Mountain formations are largely of Proterozoic age. Smaller patches of Proterozoic rocks come to the surface in the Adirondacks of northern New York, in the Black Hills of South Dakota, and in other regions.

The sequence of events during Proterozoic time is best known in the region about Lake Superior. This is briefly as follows:

1. *Lower Proterozoic formations* are best preserved in the territory north of Lake Huron. These rocks, which go by the name Huronian, were laid down on the eroded schists and granites of the Archeozoic. They consist largely of coarse sedimentary rocks (conglomerates and quartzites) with some slate, dolomite, and interbedded lava flows. Later igneous intrusions have metamorphosed some of the Huronian beds into schists and marble. Most of the rocks of this system are highly folded. A notable feature of the Lower Huronian is the presence of a conglomerate over a wide area in southern Canada which is of undoubted glacial origin. The bowlders in this formation are in some cases of huge proportions and have the subangular forms and unassorted arrangement of more recent glacial deposits. Some of the pebbles and bowlders show the striated surfaces so characteristic of glacial débris, and in places remnants of old land surfaces scoured and grooved by

the moving ice have been detected. These deposits extend over an area of more than half a million square miles and indicate the existence of a glacier of continental proportions at a time when, according to one view of the earth's origin, the globe was still very hot. The presence of a large ice cap at this early date, now a well-substantiated fact, strongly favors the planetesimal, or "cold-earth," hypothesis of earth origin advanced by Chamberlin.

In Ontario a great thickness (20,000 feet) of cleanly washed white sandstones, with some arkose and conglomerate, was deposited in Lower Proterozoic time. These rocks are known as the Sudbury formations. Some geologists consider these strata to be of Archeozoic age, but most correlate the Sudbury with the early Huronian strata farther west.

2. *Middle Proterozoic time* is represented by a series of sedimentary rocks and interbedded lava flows in the Lake Superior region, similar to the underlying formations but not so highly folded and metamorphosed. The two rock systems are separated by an unconformity which indicates a long, lost interval of time after the deposition of the Lower Proterozoic sediments, when they were uplifted and subjected to erosion. The Middle Proterozoic formations, known variously as the Animikean and the Upper Huronian, are of great importance because they contain the largest rich deposits of iron ore in North America. During this time sediments rich in iron were deposited, presumably with the aid of bacteria; and later the iron was concentrated into an ore by the work of ground water, which leached out the impurities (mainly silica) and left behind a residue of nearly pure iron oxide. Iron ores of this age are mined extensively in northern Minnesota, Wisconsin, and Michigan, and furnish by far the largest part of the iron used in this country.

3. *Upper Proterozoic time* is best recorded in the Lake Superior region in a system of rocks called Keweenawan, separated from the underlying Middle Proterozoic by an unconformity. They differ from preceding Proterozoic systems as well as all subsequent systems in possessing the thickest accumulation of lava

flows ever known to have been laid down in a single locality. The Keweenawan lavas are thirty-five thousand feet thick in the aggregate; nobody knows how many distinct flows are represented. With the lavas are associated fifteen thousand feet of sedimentary beds, chiefly sandstones and conglomerates.

The Keweenawan system is important economically because it contains the world's most valuable deposits of native copper. This copper, which is thought to have originated in waters associated with the lava flows, is found in the pores and gas cavities of some of the flows and in the spaces between the grains and pebbles of the associated sandstones and conglomerates. As was the case with the Middle Proterozoic iron formations, the copper was redistributed and concentrated by underground water. The copper mines of northern Michigan are among the oldest mines in North America, having been worked by the Indians long before the coming of the white man. Of no less importance are the rich silver and nickel ores of Ontario, formed in conjunction with igneous upwellings of late Proterozoic age.

While igneous activity was writing the history of Upper Proterozoic times in the Canadian Shield area of east-central North America, quiet deposition was the order of the day in western Montana, eastern Idaho, and British Columbia. Over thirty-seven thousand feet of sandstones, shales, and other sediments, known as the Belt series, were accumulated. Although a few lava flows and dikes are associated with Beltian rocks, the most striking peculiarity of these formations is the scarcity of igneous materials. In the region cut by the Colorado River twelve thousand feet of Proterozoic rocks equally free from igneous materials are exposed.

The Proterozoic ended everywhere with uplift and a long period of erosion. It is difficult to estimate the interval between the Proterozoic and later times, because, like the Archeozoic, the Proterozoic formations contain very few fossils through whose study the geologist looks for evidence as to the length of time involved in the "missing links," or unconformities, which occur throughout the geological record. We shall see in Chapter VII that the life record of the pre-Cambrian eras is so poor that no generalization concerning the state of evolution in either the plant or the animal kingdom can be made with certainty. It is known, however, that the rocks of the Paleozoic were deposited on the old Proterozoic lands over a distinct unconformity, and are teeming with a varied and highly developed fossil fauna which demands long ages of previous history to have developed such advanced forms from the low life-jelly which must have preceded. Many scientists believe that much of this evolution took place during the Proterozoic-Paleozoic interval and accordingly believe that the time represented by the break was very long — perhaps as long as, or longer than, all time which has elapsed since then.

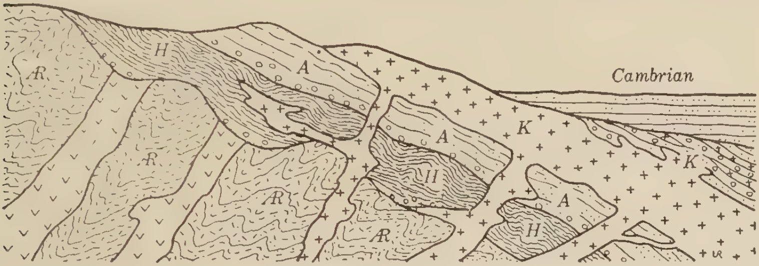

FIG. 175. Diagram showing the relation of the Archeozoic and the Proterozoic rocks in the Lake Superior district. (Modified from Chamberlin and Salisbury)

AR, Archeozoic; *H*, Huronian; *A*, Animikean; *K*, Keweenawan

Summary of pre-Cambrian events. The table on page 248 gives a tabular résumé of the most important happenings of pre-Cambrian times. It must be remembered that the rocks of these remote eras are the most difficult to interpret of all rocks in the earth's crust, since they not only were disturbed and altered by the violent vulcanism and diastrophism of their day, but suffered all the vicissitudes which harassed the earth's crust during subsequent eras of time. Although these formations are largely metamorphosed, broken, and crumpled, in some cases even beyond recognition, they at least tell the story of vast eras of time — so vast that the human mind cannot comprehend their significance, so vast that all later events are dwarfed into the appearance of a small and insignificant appendage upon the main body of earth history.

PRE-CAMBRIAN TIME		
ERA	PERIOD	EVENTS
Proterozoic	Upper Proterozoic	Great vulcanism in central and eastern North America with copper, silver, nickel, and other deposits. Quiet deposition in western North America
	Unconformity	Records lost
	Middle Proterozoic	Great iron deposits
	Unconformity	Records lost
	Lower Proterozoic	Earliest glaciation
Archeozoic	Great unconformity	Records lost
	Laurentian	World-wide igneous intrusion
	Keewatin	World-wide igneous extrusion alternating with sedimentation

THE PALEOZOIC ERA

No more profound break exists in the entire geological record than that which separates the pre-Cambrian and Paleozoic ("ancient life") systems of rocks. The latter are strongly contrasted with the former in being (1) far less faulted, folded, and metamorphosed and (2) in bearing an abundance of fossil remains. The physical history of the Paleozoic era in North America is largely one of repeated invasions of the continent by shallow shifting seas: an ebb and flow of marine waters in and out of shallow basins on the surface of the continental mass.

The Canadian Shield, which is the seat of greatly prolonged deposition and which was punctured by repeated intrusions of igneous material during the pre-Cambrian eras, became a land area at the end of the Proterozoic, and there is no evidence to show that it was ever again depressed below the level of the sea. South and west of this land area all that part of North

America which is now dry land stood at or slightly below sea level throughout most of the Paleozoic era. Because of the low-lying nature of the continent during that time, the sea was often able to encroach on the land and leave there a record of its several visitations in the form of a variety of sedimentary deposits.

Certain areas were more depressed than others, and it was in these geosynclinal basins that the most continuous record of Paleozoic events was preserved. To the east and west of the present borders of the continent stood the hypothetical old lands of Appalachia and Cascadia, which suffered erosion during most of Paleozoic time and furnished the sediments that were laid down in the long troughs at their inner bases (Fig. 176). These great troughs were roughly parallel to the borders of the present continent and were the seats of deposition during most of the Paleozoic era. The western, or Cordilleran, geosyncline opened on the south to the Pacific Ocean and on the north to the Arctic Ocean, and occupied portions of what is now Mexico, Lower California, California, Nevada, Utah, Idaho, Wyoming, Montana, British Columbia, Alberta, Yukon, and Alaska; the eastern, or Appalachian, geosyncline occupied portions of what is now Mississippi, Alabama, Tennessee, Kentucky, West Virginia, Pennsylvania, New York, Vermont, Quebec, and Labrador, and opened on the south to the Gulf of Mexico and on the north to the Atlantic Ocean.

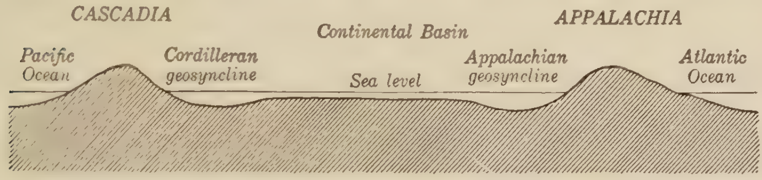

FIG. 176. An east-west section of North America, showing general conditions during the Paleozoic epochs of submergence

Between these two great troughs south of the Canadian Shield, which bulk so large in geological history because each saw the birth of a great mountain chain (the Rocky Mountains and the Appalachian Mountains respectively), was the low continental basin area which never during the Paleozoic stood very high above sea level. From time to time the outer oceans found their way into the interior of the continent by following the depressions of the two great geosynclines. During several epochs the depression of the interior area by earth movements made it possible for marine water to leave the marginal troughs and spread over the intervening territory. Again and again during Paleozoic time did such seas advance and retreat, bringing with each new invasion a new record of sedimentary deposits and life. By unraveling the history locked up in the deposits of these transitory seas the following story has been gleaned.

Cambrian time. Largely because of the prolonged erosion which followed the Proterozoic, untold millions of tons of rock débris were transferred from the lands to the seas, causing the latter to swell and enter the lowlands of the continental masses. In North America the marine waters of the Arctic, Pacific, and Atlantic oceans, as well as the Gulf of Mexico, advanced into the great marginal troughs previously described and thence spread into the interior lowlands. From a study of the sedimentary deposits left as records of this invasion it is known that in early Cambrian time the seas were confined to the Cordilleran and Appalachian geosynclines. By Middle Cambrian time the marine waters still occupied the western basin, but withdrew from the eastern trough with the exception of a limited area along the present eastern margin of the continent. In Upper Cambrian time the waters spread eastwardly from the Cordilleran trough across the southern margin of the continent and thence northward as far as Lake Superior. Somewhat later the Appalachian geosyncline was refilled with water which spread to join the embayment from the west. Finally the waters in the Cordilleran trough completely withdrew, leaving the continent emergent at the end of the period, with the exception of the Appalachian basin area and a central embayment which extended as far west as Nebraska and Arkansas.

From this description it can be seen that although during the Cambrian period the continent of North America suffered widespread submergence from invading marine waters, followed by marked but not complete emergence, the seas were of a shifting nature and moved about on the surface of the land much as water on the surface of an oilcloth can be made to move and vary its outlines if we wrinkle the oilcloth. The gentler type of diastrophism consists of earth movements which warp the surface of the land and, by continually shifting the position of areas that are relatively low and high, cause the marine waters which have crept in from the oceans to be shifted accordingly. The Cambrian seas of invasion are typical of other similar bodies of water which many times during geological history visited the several continents of the earth and left behind deposits of sedimentary material to tell the story. Such bodies of marine water are called *epeiric* seas.

The most significant feature of the sediments deposited in Cambrian seas is the abundant evidence of life preserved by the fossil remains in the rocks formed during this period. The pre-Cambrian rocks are nearly devoid of fossils, although a few are known and prove that life existed on earth at that remote time. That the shallow seas of the Cambrian teemed with life cannot be doubted, and, as we shall see in the next chapter, the creatures that lived at this time were so highly organized that they must have had a long ancestry behind them and can in no sense be thought to represent the first life on earth.

The Cambrian sediments are naturally thickest in the areas formerly underlain by the great geosynclinal troughs, for here the seas were present for a longer time than in the interior and were nearer the source of supply for waste rock material (the old land masses of Cascadia and Appalachia). Here and around the edges of the Canadian Shield the Cambrian rocks can be observed. On the whole, however, the deposits of Cambrian time are deeply buried under later formations and come to the surface only in regions that have undergone folding and deep erosion. We have already emphasized the importance of the great unconformity which nearly everywhere separates unfossiliferous Proterozoic rocks below from the highly fossiliferous Cambrian formations above.

Cambrian time was a time of quiet in North America, for only minor warpings of the crust occurred and vulcanism was almost entirely absent. The climate of the Cambrian was universally mild, inasmuch as certain coral-like animals that could not have lived in cold water attained a world-wide distribution, even to the extent of existing in the polar regions. The abundance of limestone formations indicates equable seas at this time, since it is known that limestone, which is today being formed in tropical seas, cannot accumulate to any great thickness in cold water. On the whole the Cambrian landscape in North America was monotonous, since, with the exception of the highlands which bordered the continent, the great bulk of the land was low-lying and rolling, and vast areas were covered with shallow bodies of marine water.

The close of the Cambrian was marked by a quiet emergence of the continents and an absence of mountain-making movement. We have seen that some parts of North America remained submerged at this time, and it would seem that in such areas deposition continued without a break into the next period. In these regions no unconformity exists between Cambrian and Ordovician formations, so that it is exceedingly difficult for the geologist to determine where the one system ends and the other begins.

Ordovician time. During Ordovician time North America was thrice inundated by warm marine waters, mainly from the Arctic Ocean. The first inundation of Lower Ordovician time spread from Labrador and Newfoundland into the Appalachian geosyncline and thence across Oklahoma and Texas into the southern part of the Cordilleran trough. There is no evidence that the middle of this basin was under water at this time, although the northern part was covered by a sea which came in from the north, across northern Greenland and the Arctic islands, as far south as northern British Columbia. Much of the Lower Ordovician sea was later converted into

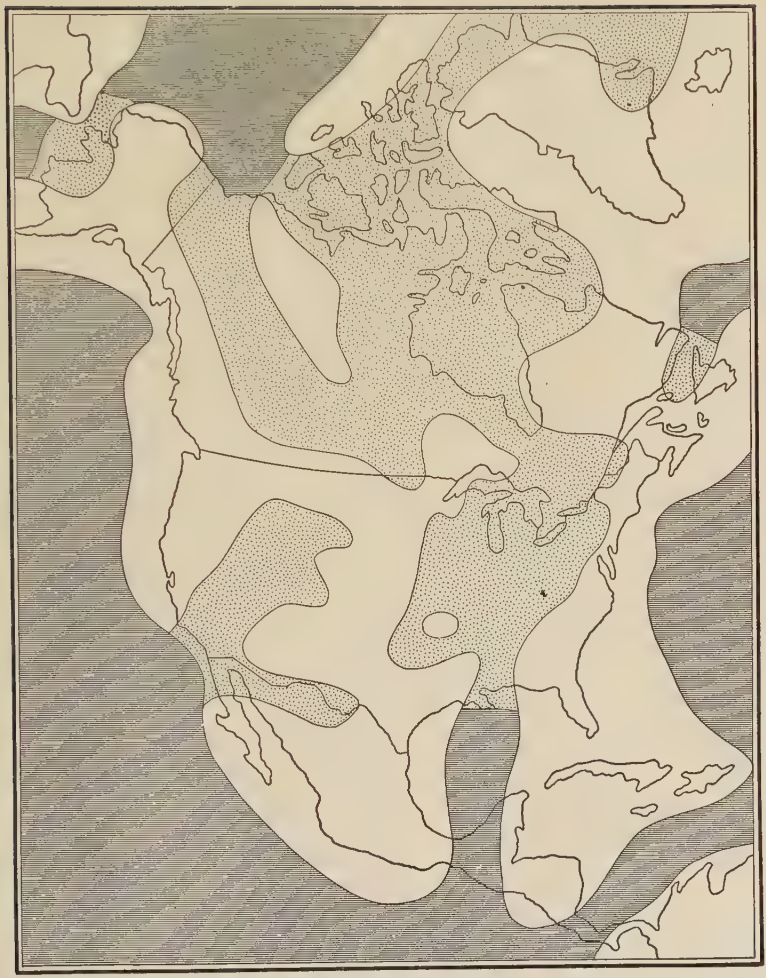

FIG. 177. Paleogeographic map of North America, showing the extent of the great flood of the Middle Ordovician. (Reprinted by permission from "Textbook of Geology," by Pirsson and Schuchert. Published by John Wiley and Sons, Inc.)

Oceans, ruled; lands, white; epeiric seas, stippled land which suffered intense erosion, particularly in certain parts of eastern North America. The second flood, of Middle Ordovician time, was the greatest ever suffered by the North American continent. A great sea spreading from the Arctic Ocean joined another entering from the Gulf of Mexico; still a third entered the Southwest from the Pacific Ocean, but was apparently never joined to the other embayments. Together these seas covered about 60 per cent of the continent. At the close of Middle Ordovician time the seas withdrew, but again advanced in Upper Ordovician time into approximately the same territory occupied by the preceding invasion, but this time covering about 40 per cent of the continent. At the close of the period all North America was emergent with the exception of a small area round the Gulf of St. Lawrence.

The Ordovician period is noteworthy because the shallow seas which invaded the continents during this time were exceptionally oscillatory. Although North America was the site of three marine invasions and withdrawals, and the organisms which the sea brought with it differed somewhat with the different invasions, these organisms were nevertheless bound together in a general similarity. For this reason it is agreed to include all three invasions in the Ordovician period instead of erecting a distinct period for each.

The sediments deposited in the epeiric seas were varied; but since the lands were unusually low during this period, especially during Middle Ordovician time, little coarse sediment was furnished to the seas, and as a consequence the deposits consisted largely of limestone and shale. Great hordes of lowly marine creatures swarmed in the warm, clear seas of Ordovician time and left an abundance of fossils entombed in the sediments to commemorate their existence.

The Ordovician was of longer duration than any other Paleozoic period, but throughout the history of this period in North America evidence of igneous activity is conspicuously absent. In the British Isles, however, thick masses of volcanic ash and lava of Ordovician age bespeak intense vulcanism at this time. The uniformity and abundance of the fossil remains show that the climate during this period was a continuation of the mild conditions which obtained during the Cambrian. The Ordovician closed with a general uplift and local mountain-building in eastern North America and western Europe.

Silurian time. Throughout New England and eastern Canada the mountains made at the close of the Ordovician period were worn down by erosion, and the epeiric sea which again invaded the continent during the initial epoch of Silurian time deposited sediments unconformably upon the old worn-down Ordovician mountains. In the interior region, where the withdrawal of the Ordovician seas was occasioned by gentle uplift of the land without folding, the Silurian deposits lie in conformable relationships with the strata below. The separation of the systems here must be made on the basis of the differences between the fossil remains of the older formations and those of the younger.

The Silurian deposits in North America tell the story of a single cycle of oceanic spreading and retreating. Like the Ordovician seas, the Silurian seas came from north, south, east, and west, and by Middle Silurian time had submerged about 35 per cent of the continent. The Middle Silurian, like the Middle Ordovician, was a time of clear seas and extensive limestone-building. The climate continued mild over most of the earth. The coral, a faithful indicator of warm water, has been found in rocks of Silurian age within nine degrees of the north pole. Furthermore, toward the end of Silurian time extensive deposits of rock salt were formed in eastern North America, which proves that the climate became actually arid, so that salt was made to precipitate by the excessive evaporation of the sea water in the shallow depressions. The Silurian period, like the Cambrian and Ordovician periods before it, was a time of crustal stability, almost devoid of igneous activity until its closing epoch.

At the end of the Silurian, however, the stresses which had been stored for so long in the interior of the earth found relief in crustal shortening by folding and thrusting in many parts of the world. Mountains built at this time extend from Scandinavia through the Scottish Highlands and England into France, Spain, and Africa. During this epoch folding likewise occurred in the rocks of the island of Spitzbergen, extending across Greenland into North America. There was folding also in South America, Australia, and Siberia. Great overthrust faults which shortened the crust more than eighty miles characterized this epoch in Scotland. Volcanoes, too, originated and gave off vast quantities of lava and ash. These "Caledonian" mountains, which in their day must have rivaled the Alps for splendor, were reduced to flatness and covered by the sea before the close of the Paleozoic era.

Devonian time. The great mountain-building movements which distorted Silurian sediments in so many regions at the close of that period were not felt over the largest part of North America. Consequently, when the Devonian seas crept in over the continent, they deposited their sediments conformably upon the older Silurian formations. Somewhat more than one third of our continent was inundated at this time by seas which came in mainly from the Arctic Ocean. The marine creatures found in North America in rocks of Devonian age resemble those in Europe and Asia in rocks of corresponding age, so that, as was the case during the preceding periods, the Devonian saw a progressive widespread submergence of all continents in the Northern Hemisphere. South America, likewise, was partly submerged, and a tropical sea spread from the south into North America by way of the Appalachian trough during Middle Devonian time, carrying with it certain characteristic marine shells which are now to be found in Devonian rocks of both western continents. Africa and Australia also were the sites of marine invasions during this period.

Among the most interesting deposits of this period are those in northern England, Wales, Iceland, and Scotland, known collectively as the Old Red Sandstone. Although considerable controversy concerning the exact origin of these deposits has taken place, it is generally believed that they are of continental and not marine origin. Formerly they were thought to have been deposited in fresh-water lakes, but many geologists now believe them to have accumulated on the flood plains of rivers, partly under the action of torrential waters and partly through the agency of wind. These beds are the result of the erosion of the old Caledonian mountains and probably represent that part of the rock waste which failed to reach the sea, but lodged instead in the depressions between the several ranges of the old mountains. Similar terrestrial deposits are known in Russia, Norway, Nova Scotia, and the island of Spitzbergen. The Old Red Sandstone has yielded some of the earliest known land plants, as well as several types of primitive fresh-water fishes. The preponderantly red color of much of the "Old Red" proves that long exposure to the atmosphere thoroughly oxidized the iron compounds which provide the color pigment in most rocks. Marine sediments, protected from the atmosphere by the water in which they are deposited, seldom are of a red color.

Toward the close of the Devonian a large part of Maine, Quebec, New Brunswick, and Nova Scotia was uplifted and folded. Extrusions of lava and granitic intrusions characterize this epoch in these regions. Mount Royal, from which the city of Montreal is named, is the eroded stump of a late Devonian volcano. Local mountain-building and vulcanism in Great Britain, France, and Germany likewise marked the close of the Devonian, but were not restricted to this epoch in these regions, since thick volcanic deposits of Lower Devonian age are also known. In North America, with the exception of the region mentioned, the Devonian closed quietly without folding or vulcanism.

Mississippian time. The erosion that followed the building of mountains in the Maritime Provinces of Canada and northern New England furnished sediments which were carried by streams to the west and south and deposited on the marine formations of Upper Devonian age. The Catskill formation, which today forms the principal part of the Catskill Mountains in southeastern New York, is the landward portion of a great delta formed at this time out of the rock waste carried by rivers from the mountains to the northeast. This formation is usually referred to the Devonian, although it represents an event which took place during the interval between two periods, when the land was suffering erosion. Such intervals, as we have seen, are usually marked by an unconformity, but in the case of the Catskill formation we have one of the few exceptions to the rule.

The Mississippian proper opened with an incursion of marine waters which spread over large areas in North America, England, France, Russia, central Asia and northern China, Australia, Argentina, and Chile. During this period the lands were generally low-lying and the seas teemed with a variety of living creatures. In North America much the same conditions that obtained in the Devonian prevailed throughout the Mississippian. Most of the sediments were of marine origin; in many areas they were laid down conformably on the undisturbed Devonian beds. At the close of the period the marine waters withdrew largely from the continents without any attendant earth movements of wide importance. The formations of this system are characterized by many minor unconformities but by no breaks of large significance, so that the Mississippian period must have been a time of many minor warping movements in the crust of the earth, which caused the epeiric seas to shift continually. At the close of the period local mountain-building movements took place in Oklahoma, eastern Canada, and central Europe.

Pennsylvanian time. Pennsylvanian time saw an innovation in the monotonous course of Paleozoic events. Epeiric seas, coming chiefly from the southwest, invaded the continent of North America during early Pennsylvanian time. These seas were very oscillatory, advancing upon and withdrawing from the very flat lands many times during the course of the period. When the sea left the land, broad swamps profuse with vegetation were formed. In these swamps carbonaceous material accumulated, so that when the sea again advanced over them, layers of sediment were deposited over plant material, which was gradually changed into seams of coal. Coal swamps were most common in the eastern part of North

America during Upper Pennsylvanian time, and here there occurred fewer marine invasions and consequently thicker and more numerous beds of coal. Swamp conditions were widespread over Pennsylvania, West Virginia, Ohio, Tennessee, and Illinois during this period, and the most valuable coal in the world was accumulated. Farther west marine conditions were more persistent, and even where continental sediments were deposited, no coal was formed. Pennsylvanian coal deposits are not restricted to North America, but are also found in China, Asia Minor, and Siberia.

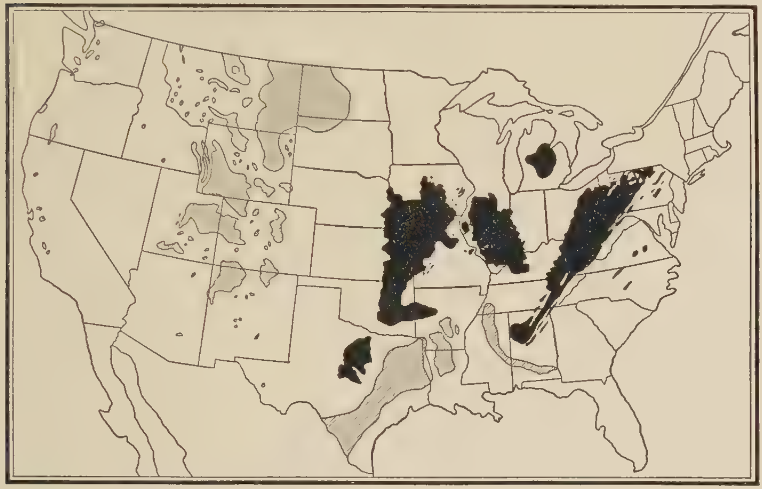

FIG. 178. Map showing the distribution of coal in the United States. (Courtesy of the United States Geological Survey)

Coals of Pennsylvanian age, black; coals of other ages, ruled

The Appalachian geosyncline, which patiently received the sediments carried to it by sea and rivers throughout early Paleozoic time, now began to manifest decided unrest. Some indications of this had already appeared in the folding that terminated the Devonian in eastern Canada. Thick formations of coarse sediments of early Pennsylvanian age in the Appalachian region indicate uplift and quickened erosion in this area at the close of the Mississippian. Disturbances in the

Appalachian trough increased to Middle Pennsylvanian time, when the anthracite coal of Pennsylvania was produced by the intense heat and pressure engendered by the folding of the rocks containing seams of carbonaceous material. Whereas diastrophism was active in the Appalachian trough to the close of the period, the Pennsylvanian is unique in that the most intense uplift and folding came during the middle of the period. Similar mountain-building movements took place at this time in western Europe and Russia, when the Hercynian Mountains were formed. Mountain ranges extended from England through France to Spain, trending in a general southeasterly direction and converging in Spain and northern Africa with another arm of ranges trending in a general southwesterly direction from Belgium through Germany and Switzerland. These mountains are sometimes called the Paleozoic Alps, and although the folding which produced them did not all come during this epoch, they were greatly elevated during mid-Pennsylvanian time. Much later they were again folded and reëlevated, and part remains as the famous Alps of the present period.

Permian time. Permian time is of great significance, since it marks the transition from the Paleozoic era to the Mesozoic. In North America the old Carboniferous seas began to withdraw from the Great Plains area during Lower Permian time, and since the climate was arid, a large quantity of salt and gypsum was deposited during the process. The Permian in the west was in the beginning very similar to the Pennsylvanian, and the beds of the former are of marine origin and overlie the latter conformably. As the seas withdrew, however, lagoons occupied by steadily shoaling waters deposited under an arid climate not only salt and gypsum but red sediments of great thickness which show the effect of exposure to atmospheric conditions. In the east during the Lower Permian the lands stood so high that almost no deposits were formed. By the end of Lower Permian time the seas had entirely withdrawn from the continent, and erosion had become the dominant geological process. This was furthered by uplift in several regions: notably in Colorado, where the "Ancestral Rockies" were forming; in Arkansas and Oklahoma in the Ouachita Mountains; and especially in the Appalachian geosyncline, all the way from Newfoundland to Alabama. This mountain-building, as we have seen, began at the close of the Mississippian, was at its peak in the middle of the Pennsylvanian, but did not reach its termination until the Permian period.

We have seen that during most of Paleozoic time the old land mass of Appalachia to the east of the present continent of North America had been furnishing sediments to be deposited in the great Appalachian geosyncline. With the exception of a few local uplifts at the close of the various periods, the sediments in this trough accumulated until a thickness of nearly six miles had been attained by Permian time. We have already seen why geosynclines are areas of weakness in the earth's crust. The stresses which had accumulated through the long periods of the Paleozoic era were relieved throughout the Appalachian trough during the Permian. The great thicknesses of sediments were folded and elevated into a mountain system of majestic proportions. The building of these mountains in North America marked the close of the Paleozoic era and stands out as the most conspicuous and important geological event of the entire era.

The profound uplift which affected North America at the end of the Paleozoic was also operative at this time in Europe. The folding of the Hercynian Mountains of Europe and Africa during the Middle Pennsylvanian was continued into Permian time. Volcanic activity, noticeably slight in North America, was widespread during parts of the Permian in Europe. In Germany during the Upper Permian the greatest salt deposits in the world were formed, an example of the extreme aridity of certain parts of the earth during late Paleozoic time. Coal-producing swamps, which were most important in America during the Pennsylvanian and in Europe during the Mississippian, still existed during the Permian (notably in Australia) but on a reduced scale.

Perhaps the most remarkable feature of the Permian period is the evidence of world-wide glaciation during this time. At the close of the Lower Permian nearly all the continental areas were dry land. Glaciation followed diastrophism in most of the regions affected, and although it did not affect all continents at exactly the same time, the epochs from middle to late Permian were characterized by glaciation in many parts of the earth. The most remarkable feature of Permian glaciation is that it visited the equatorial lands of the globe and was to a large extent localized in a zone on both sides of the equator within thirty degrees of it on either side. Australia, South America, India, and Africa were glaciated on a large scale; England, France, eastern Massachusetts, and other scattered areas, on a smaller scale. In South America and Australia the glaciers were of continental proportions, and are known to have reached the level of the sea, because their deposits are interbedded with marine formations. In Australia the surprising combination of glacial deposits, marine formations, and coal beds occurs. While much of the evidence of these ancient glaciers is obliterated, enough remains to prove that in extent they equaled, if they did not exceed, any other glaciers before or since. It is all the more remarkable that they should have formed in regions of low latitude and, at least in some instances, at low altitudes as well. The deposits left behind are those typical of present glaciers: unassorted bowlders, some bearing striæ and resting on grooved and polished floors, associated with much finer clay produced by the grinding action of the moving ice.

Conclusion of the Paleozoic. The unusual events of the late Paleozoic, particularly the Permian period, had a profound effect upon living things. Many groups of organisms which had thrived in the warm Paleozoic seas were sadly depleted by the refrigeration of air, land, and water that came as the natural result of widespread glaciation. Some great groups became entirely extinct. The old types of land plants which furnished material for the coal deposits suffered extremely, and an entirely new flora, adapted to withstand cold, was evolved.

The several changes which the earth underwent during the Permian — changes which furnish good reasons for making that period the closing period of the Paleozoic era — are as follows: (1) world-wide uplift and mountain-building followed by erosion, (2) profound changes in the life of land and sea, (3) widespread glaciation, and (4) widespread aridity. Such changes as these resulted from the yielding of the earth's crust to stresses accumulated for a long time.

Summary of Paleozoic events. The physical history of the Paleozoic era may be tabulated as follows:

THE PALEOZOIC ERA

Period	Events
Permian	World-wide uplift, mountain-building, glaciation, and aridity
Pennsylvanian	World-wide uplift; the formation of the world's greatest coal deposits in North America
Mississippian	Coal swamps in Europe; low lands and warm, clear epeiric seas in North America; many minor unconformities
Devonian	Progressive widespread submergence of continents; terrestrial deposits on large scale; local diastrophism and vulcanism at close
Silurian	Single cycle of marine transgression; mountain-building in many parts of the world at close
Ordovician	Three cycles of marine inundation in North America, including the greatest submergence of all time; intense vulcanism in the British Isles; local mountain-building in North America at close
Cambrian	First abundantly fossiliferous rocks; low lands; mild climate; no mountain-building movements

THE MESOZOIC ERA

After the wholesale slaughter of life at the close of the Paleozoic the earth became populated with new dynasties, which were destined to dominate the stage of life during the Mesozoic ("medieval life") era. The seas of the early Paleozoic era were ruled by great hordes of simple creatures without backbones, but these gave way with the late Paleozoic and

Mesozoic to the dominance of higher creatures, fishlike and reptilian, possessing backbones. Although the life of the Mesozoic represents a great advance over the creatures of the early Paleozoic, it nevertheless was less highly developed than that of more recent geological time. For that reason it has been called medieval, and the rocks in which the records of this medieval life are preserved are named after the life, although in this connection it must be remembered that Mesozoic time stands much closer to the present period than to the remote and obscure ages of the Archeozoic, where life is first known.

Triassic time. After the world-wide revolution at the close of the Paleozoic all continents stood high and suffered erosion.

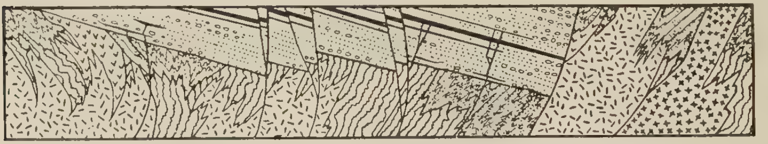

FIG. 179. Cross section of a Triassic basin (Connecticut valley), showing the faulted and peneplained condition of the formations as they appear today. (After Barrell)

The Triassic period, which initiated Mesozoic time, is largely represented by beds of red sands and clays deposited on the land by rivers. In North America such continental deposits occur in long, narrow belts parallel to the Atlantic coast and extending from Nova Scotia to central North Carolina, in basins which developed to the east of the newly formed Appalachian Mountains. Although these deposits are several thousand feet thick, they nowhere show any evidence of being deposited in an epeiric sea, but are everywhere clearly the result of rivers bringing coarse sediments from the highlands to the west and depositing them in the basins at their foot. These basins were formed by normal faulting, probably the result of readjustment after the main paroxysm of the Appalachian revolution. Much volcanic activity as well as igneous injection kept pace with deposition in these basins, and it was at this time that the great sill which forms the Palisades of the Hudson River came into being.

Although marine deposits of Triassic age are totally lacking in eastern North America, during the early epoch of the period the sea invaded California, Nevada, Oregon, Utah, and Idaho from the Pacific and laid down several thousand feet of calcareous marine sediments. Later the sea spread both north and south, into Alaska as well as into Mexico, while at the same time an embayment from the Arctic left records in northern Greenland and the Arctic islands. One of the most striking features of the Triassic in western North America was the great number of volcanoes in Alaska, British Columbia, and California which threw out great quantities of lava and ash, forming deposits several thousand feet thick.

In Europe both continental and marine deposits of Triassic age are of widespread occurrence. The threefold division of these formations in Germany gives the name *Triassic* to the system. Salt lakes and general desert conditions were widespread in Europe at this time. From the prevalence of salt, gypsum, and red rocks we infer that the case was the same in America.

Jurassic time. The emergent condition of the continents during the Triassic period continued into the Jurassic. Erosion continued to be the dominant geological process. In North America seas were present along the Pacific border of the continent from Mexico to Alaska, and their deposits give abundant evidence of life. The remainder of the continent was emergent, and not a single deposit, either continental or marine, can be unquestionably referred to this system in any of the territory east of the Great Plains. The volcanoes of the Pacific coast born during Triassic time continued with renewed vigor throughout the Jurassic.

Large areas in Europe and Asia were submerged by the sea during the progress of the Jurassic period; by Upper Jurassic time this flood had reached its maximum. It stands as one of the greatest submergences of Eurasia in all geological history. Much of the British Isles, France, Germany, Spain, Russia, Siberia, and northern India were under water at this time. Great geosynclinal troughs were the sites of heavy sedimentation. Perhaps most important of all was the great trough out of which the Himalaya Mountains were destined to rise at a later period.

The close of the Jurassic was marked in North America by folding in the Cordilleran geosyncline and by the initial uplift of the Sierra Nevada, the Coast Ranges, and the Cascade and Klamath mountains of the Pacific coast. During this folding great upwellings of magma, which formed giant batholiths along the entire length of the Pacific coast from Lower California to Alaska, marked the world's greatest epoch of igneous activity since the Archeozoic. The Coast Range batholith in British Columbia and Yukon, of Jurassic age, is over a thousand miles long and is the largest intrusive mass exposed by erosion anywhere in the earth's crust.

Lower Cretaceous time. With the folding in the Cordilleran trough at the close of the Jurassic, another great geosyncline formed along the entire Pacific coast of North America to the west of the Cordilleran region and became filled with marine waters during Lower Cretaceous time. During the same period a marine embayment entered the United States from Mexico across Texas as far as Kansas and Colorado. A slight area of sedimentation extended along the Atlantic seaboard in which river deposits were accumulated and preserved. A large part of the present Great Plains area in Wyoming, Montana, and South Dakota and much of the territory now occupied by the Canadian Rockies were the sites of poorly drained swamps where great thicknesses of fresh-water deposits and not a little coal accumulated. Here lived the great plant-eating dinosaurs, the largest animals that ever inhabited any land. In Europe the Lower Cretaceous deposits are, as in North America, rather well developed and of both marine and continental origin. A general uplift without mountain-building terminated the Lower Cretaceous; this was especially well marked in western North America, where Lower and Upper Cretaceous formations are unconformable.

Upper Cretaceous time. The widespread erosion which characterized the early periods of the Mesozoic era succeeded in

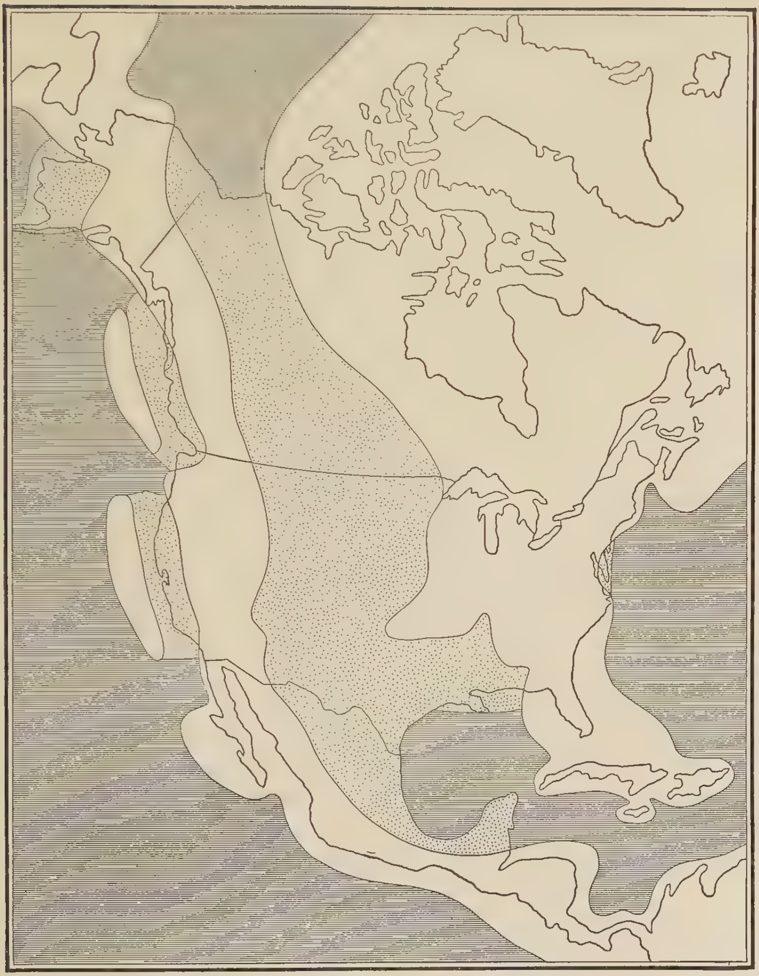

FIG. 180. Paleogeographic map of North America, showing conditions at the beginning of Upper Cretaceous time. (Reprinted by permission from "Textbook of Geology," by Pirsson and Schuchert. Published by John Wiley & Sons, Inc.)

Oceans, ruled; lands, white; epeiric seas, stippled. Note the two great longitudinal embayments reducing to near flatness many large areas in various parts of the world. The marine invasions of the Lower Cretaceous gave warning that the pendulum was beginning to swing from erosion to deposition. During the Upper Cretaceous all the continents suffered one of the most important and widespread submergences of all time. In the first epoch of this period a great interior sea cut a wide swath across west-central North America from the Arctic Ocean to the Gulf of Mexico, sending out a smaller tongue which covered the Gulf and Atlantic coastal plains. Another sea invaded the Pacific-coast region but never penetrated far inland. At the same time large tracts in South America, Europe, Asia, and Africa were beneath the sea. The great beds of chalk formed during the Upper Cretaceous are the most characteristic feature and the one for which the system was named. The best-known chalk deposits of this age are the cliffs of Dover, England, and those across the English Channel in northern France. In the United States Cretaceous chalk occurs extensively in Nebraska, Texas, Colorado, and Kansas.

At the end of the Upper Cretaceous and continuing into the early Tertiary epochs a world-wide uplift of all the continents took place, together with intense mountain-folding along great but restricted belts. The Cordilleran geosyncline, which had been receiving sediment continually since Cambrian time, was uplifted, and its thick deposits were folded and faulted from Alaska to southern Mexico. The resultant mountains were the Rockies, which, although they had begun to rise before the close of the Mesozoic and continued to rise after it, attained their main growth at this time. The Andes of western South America, the longest unbroken mountain chain in the world, rose at this time out of a geosynclinal basin which, like that of the North American Cordilleran trough, had been receiving sediments since the beginning of the Paleozoic era. The Appalachian Mountains, which by the end of the Jurassic had been peneplained, were uplifted about fifteen hundred feet at the end of the Upper Cretaceous without thrusting or folding. Uplift affected many other land areas, and the foundering of certain hypothetical continents is believed by some to have taken place approximately at this time.

The revolution which terminated the Mesozoic era was fully as intense as that which brought the Paleozoic to a close. The entire continent of North America is known to have risen vertically, and in the Rocky Mountain region, where folding and overthrusting occurred, igneous injection and volcanic eruption were accompanying phenomena. The growth and uplift of continents caused a general world-wide refrigeration of climate, although no marked glacial period resulted. As at the end of the Paleozoic, the changes at the climax of the Mesozoic wrought havoc among living creatures. Many races of animals, both terrestrial and marine, perished completely, and others were reduced in numbers. The great dinosaurs, which gave a distinctive character to the Mesozoic landscape, disappeared entirely, and the changes in the life of the sea were no less striking.

Summary of Mesozoic events. The physical history of the Mesozoic era may be tabulated as follows:

The Mesozoic Era

Period	Events
Upper Cretaceous	World-wide continental uplift; birth of the Rockies and the Andes; widespread flooding of lands; coal and chalk deposits
Lower Cretaceous	Great swamp deposits in North America; some marine flooding
Jurassic	Widespread emergence and erosion in North America; initial uplift of Cordilleran geosyncline at close
Triassic	Continental and marine deposits in North America and Europe; widespread deserts with salt, gypsum, and red beds

THE CENOZOIC ERA

The widespread flooding of the continents by ocean waters in Cretaceous time was the last great submergence in geological history. At the beginning of the Cenozoic ("recent life") era the continents stood high, and they have continued so to the present time. Although marine waters did invade the land masses during this era, they occupied marginal positions and failed to penetrate to the interior of any continent. During this era modern types of plants and animals became increasingly abundant. The general aspect of Cenozoic life is more like that of the earth today than like that of any preceding period.

Tertiary time. Tertiary time is divided into four epochs: Eocene ("dawn of the recent"), Oligocene ("little of the recent"), Miocene ("less of the recent"), and Pliocene ("more of the recent"), the terms referring to the increasing abundance in which the rocks of each series contain such shells as still live in the marine waters of the earth today.

Eocene time saw the introduction of modern types of sea shells. The marine mollusks in this series show that as many as 5 per cent of the species living in the Eocene seas are still extant. During this epoch a marginal sea inundated the Atlantic and Gulf coasts of North America as well as portions of the Pacific coast. The deposits were laid down unconformably on the older rock; in some sections along the Atlantic coastal plain they never became consolidated. The presence of coal and lignite in these marginal deposits shows that the marine waters repeatedly became shallow and gave way to swamps of brackish to fresh water, very similar to the peat bogs which exist on many low coasts today. In the western interior portion of North America extensive deposits of sedimentary material as well as some volcanic ash were laid down in lakes and on the alluvial plains of rivers which formed on the elevated bottom of the old Cretaceous inland sea. These formations attain to great thickness in places and are important because they preserve the record of the remarkable land life of the time. Great inland swamps where lignite accumulated were extensively developed in Montana, Wyoming, and North Dakota.

The continents of Europe, Asia, and Africa in Eocene time had not gone as far toward acquiring their present outlines and topography as North America had. A great expansion of the

Mediterranean Sea covered large tracts in northern Africa, southern France, Russia, Siberia, and India. The arms of this sea occupied the geosynclinal basins out of which the Alps, the Urals, the Himalayas, and the Pyrenees rose at a later date. Eocene limestones of great thickness, made up almost entirely of the calcareous skeletons of minute single-celled animals, outcrop extensively in the Mediterranean countries in Europe and Africa; these furnished the material for the great pyramid of Cheops.

The Eocene epoch was terminated by crustal movement, most pronounced along the Pacific coast of North America, where the Coast Ranges began to rise and certain older Cretaceous highlands were again elevated. The interior marshlands were completely drained at this time.

Oligocene time saw a continuation of Eocene conditions. As many as 15 per cent of the marine mollusks belonged to species still extant. Extensive erosion and local marginal seas where deposition occurred characterized all continents. Fresh-water deposits accumulated in western interior North America and preserved records of the interesting mammalian life of the epoch. Lignite, salt, and gypsum deposits of Oligocene age in various parts of Europe indicate a warm to arid climate.

In *Miocene time* the life of the marginal seas took on a strikingly modern appearance; as many as 40 per cent of the marine mollusks of this epoch belonged to species still extant. Physiographic conditions remained the same until toward the end of the epoch, when the uplifting of many regions took place. Up and down the Pacific coast the various mountain ranges suffered renewed uplift as well as faulting and folding. The main growth of the California and Oregon Coast Ranges came at this time. The Cascades of Washington were notably elevated. The present Sierra Nevada of California began to rise along the great fault of its east face, the Colorado Plateau was elevated, and the Grand Canyon of the Colorado River was begun. The Alps, the Himalayas, the Caucasus, and the Apennines, which had been areas of depression and sedimentation, were uplifted and folded into lofty mountain ranges toward the close of the Miocene. Because of these world-wide uplifts Miocene climate the world over was cooler and drier than that of the preceding epoch.

The most spectacular feature of the late Miocene disturbance was the intense vulcanism which affected most of the Pacific coast of North America. Volcanoes were numerous and contributed great thicknesses of lava and ash to the rock record of the time. The extensive lava flows of central Washington, Oregon, and Idaho were formed during this epoch. Although the Pacific coast was a region of instability, characterized by igneous activity throughout the Tertiary period, both diastrophism and vulcanism were most intense from the middle of the Miocene epoch to the end. It was then that the rugged scenery of western North America was fully evolved.

Pliocene time saw North America with nearly the same coast lines as at present. Very slight embayments from the Pacific and Atlantic oceans and from the Gulf of Mexico brought in an assemblage of marine mollusks of which as many as 90 per cent of the species were modern types. In Europe, as well as in America, lands were generally in an emergent condition during the Pliocene epoch. Erosion was everywhere the dominating geological process, just as it is today.

Quaternary time. The last period of earth history falls naturally into two epochal subdivisions: the Pleistocene ("most recent") and the Recent.

Pleistocene time was a critical epoch in the history of the earth, for the elevation of the continents which began in late Miocene time continued into the Pleistocene and caused a gradual world-wide refrigeration of climate. The culmination came with the Pleistocene glacial epoch, when about eight million square miles of the earth's surface were covered by moving ice. In North America about four million square miles were covered by sheets of ice, in some regions thousands of feet thick. A peculiarity of these continental ice sheets was that they visited the lowlands of the northeastern part of the continent in particular and avoided the highlands of the west and northwest, especially Alaska. Three great centers of ice movement existed: one over Labrador, another near the west margin of Hudson Bay, and a third over the Cordilleran region of western Canada. From these centers the glacial ice moved in all directions. During its maximum extension the southern boundary of the confluent lobes of ice formed an irregular line which passed near the sites of the present cities of Philadelphia, Louisville, St. Louis, Pierre (South Dakota), and Spokane (Fig. 181). From a study of the débris laid down by these ice sheets it is known that the margin of the ice advanced and retreated several times during the Pleistocene epoch. Intercalated with the glacial deposits are layers of clay and sand with the bones of animals and fossil remains of plants, which show that just as soon as the ice withdrew living things advanced to occupy the regions vacated. Some geologists believe that the continental glaciers of the Pleistocene advanced and withdrew as many as five times before they finally melted away. In addition to the great continental ice caps, local glaciers occupied all high mountains in northern latitudes, and separate ice caps covered Newfoundland and Greenland.

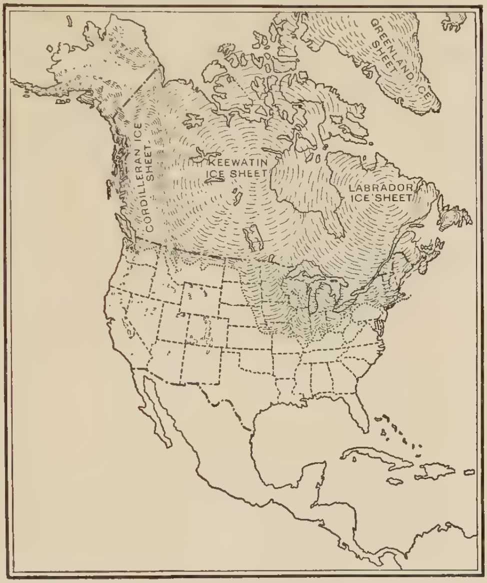

FIG. 181. Map showing the maximum extension of Pleistocene ice in North America. (After R. D. Salisbury)

The whole of northern Europe was likewise covered with ice during the Pleistocene, and the behavior of these glaciers was much the same as that of the ice sheets of North America. Iceland and Spitzbergen were deeply buried, as were the high mountain ranges of Europe and Asia. Oddly enough, Siberia was largely free from ice, due, no doubt, to the absence of enough moisture to produce glaciation on a land surface whose temperature conditions were favorable.

The effect of Pleistocene glaciation was of great significance. Many land mammals disappeared with the glacial climate, and others were driven to tropical regions, where their descendants are living today. After the ice melted away, great heaps of rock débris were left on the surface of the land, and this profoundly affected drainage. Some rivers were completely turned from their old courses, and others were greatly altered. The lobes developed by the advancing ice scoured out deep cavities, of which those in North America are now occupied by the Great Lakes. Many other smaller lakes were born in the depressions left by the ice or in basins dammed by glacial débris. Lands stood high throughout Pleistocene time, so that few marine deposits of this epoch are known. Those that do occur preserve fossils which are almost entirely of modern species.

Recent time followed the Pleistocene glacial epoch. Various estimates have placed the present day from twenty thousand to fifty thousand years from the Pleistocene. Very recent estimates by De Geer indicate that the last ice sheet left northwestern Europe from nine thousand to seventeen thousand years ago, lingering longer in some places than in others. Our proximity to the Pleistocene is likewise shown by the fact that both polar regions and all high mountains are still covered with ice. The greatest change since the days of the great Pleistocene ice caps is the rise of man and his dominance over all other creatures. How long he will rule before nature produces a higher type of organism to succeed him, nobody knows. At the most generous estimate man has been upon earth no longer than two hundred thousand years, which in comparison with the total of geological time is but a moment. It is possible that man's career on earth is still in its infancy, and that before he disappears a new chapter of mental and spiritual development will be added to the great book of life on earth.

Summary of Cenozoic events. The physical history of the Cenozoic era may be tabulated as follows:

THE CENOZOIC ERA

PERIOD	EPOCH	EVENTS
Quaternary	Recent	All continents emergent; widespread erosion
	Pleistocene	World-wide glaciation, greatest in North America and Europe
Tertiary	Pliocene	Continued world-wide elevation; restricted marginal seas
	Miocene	World-wide uplift and folding; birth of the Alps, the Himalayas, and other ranges; intense vulcanism in western North America; marginal seas and cool climate
	Oligocene	Extensive erosion; marginal seas; warm climate
	Eocene	Beginning of marginal seas and introduction of modern mollusks; extensive spreading of Mediterranean basin; uplift in western North America

CHAPTER VII

FOSSILS AND THE HISTORY OF LIFE ON EARTH

INTRODUCTION

Living and lifeless material. Thus far we have concerned ourselves almost entirely with the lifeless substances which constitute the air, rock, and water of the earth. By volume such material is of overwhelmingly more importance than that wonderful product of earth chemistry which we call life. The importance of living creatures is far out of proportion to the small space they occupy on the surface of the globe. Life is the unique factor in nature. Although the substance out of which living creatures are constructed is drawn entirely from lifeless things and can be analyzed and explained by the same methods which apply to air, water, and rock, yet the spark of animation which gives the most characteristic property to living things is a mystery that has not yet been explained by any natural law.

While many things can change the nature of lifeless material such as rock, nothing can destroy it. Its form may be altered under varying conditions, but its substance is eternal. That life property which distinguishes the quick from the clod, on the other hand, is easily destroyed, and can exist only under certain restricted conditions. Sufficient air must be present to furnish carbon-dioxide gas for plants, oxygen for animals, and water vapor for plants and animals. Temperatures must be between the freezing and boiling points of water (32° and 212° F.), because few creatures can exist long under extreme conditions of temperature. When the cold of outer space (−459° F.) and the intense heat of some stars (over 10,000° F.) are considered, the range of temperature suitable for life seems greatly restricted. Among all the celestial bodies familiar to the eye of the astronomer, the planets alone seem to present the conditions necessary to sustain life. Yet, as we look at the planets in our solar system, the limitations within this group of heavenly bodies are at once apparent. The four outer planets — Neptune, Uranus, Saturn, and Jupiter — are clearly too hot to support living things. Not only is water vapor unable to accumulate on the surface of these planets, but their substance is hot enough to render them largely gaseous. Mercury and Venus appear to present the same face always to the sun, so that their sunny sides are likely to be too hot, and their dark sides certainly too cold, to support life. Mars is thought by some astronomers to have a low type of life on its surface; others believe it to be too cold and to possess too thin an atmosphere to furnish the conditions necessary for living creatures. Unfortunately, only the other planets of our own solar system are near enough for observation, and none of them seems to possess all the prerequisites for life. It is not unlikely that the earth (at least so far as the solar system is concerned) is entirely unique in furnishing all the conditions which life requires.

The materials constructed by the life processes of plants and animals are called *organic,* because they are arranged in one or more parts called *organs,* which exist each for its special task, such as breathing, circulating blood, reproducing, digesting food, and so on. For this reason plants and animals are known as *organisms,* although in the simplest types the entire body functions as a single organ which performs all the work that is necessary to existence. As minerals and rocks, air and water, lack such organization, they are described as *inorganic.* Inorganic matter and organic matter can be contrasted as follows:

1. *Size.* With the exception of crystals, an inorganic object may be of almost any size, whereas plants and animals are definitely restricted in this regard.

2. *Form.* Inorganic objects, with the exception of crystals, may show all varieties of form, whereas each type of plant and animal is definitely restricted in form by the laws of heredity.

3. *Composition.* Inorganic substances are composed of the ninety-two chemical elements known to exist on the earth. The possibilities of combinations among these units of matter are almost limitless, and over two hundred thousand compounds are already known to exist on the earth. Organisms, on the other hand, are composed almost entirely of but six elements: carbon, oxygen, nitrogen, hydrogen, sulphur, and phosphorus. Variation in the arrangement of these elements produces all the differences which exist in the materials constituting plants and animals.

4. *Organization.* Inorganic bodies, excepting crystals, possess no high degree of organization, whereas organisms are composed of unlike parts held together by mutual interdependence. The heart is an organ of the human body; and if it is removed or ceases to discharge its duties, the body ceases to function as a living thing. In like manner each organ of a living creature is composed of many tiny cells, which are more or less dependent upon each other for their existence.

5. *Adaptation.* One of the most remarkable traits of living things is their habit of reacting to their environment. The plant that turns its leaves to the light and the insect that lays its eggs on food appropriate for its young demonstrate a characteristic possessed by all organisms but which is lacking in lifeless matter.

6. *Growth.* Inorganic substances such as crystals grow by the addition of material from the outside; all organic bodies grow from the inside by the addition of new cells between and around those already existing.

7. *Reproduction.* No inorganic body can reproduce itself, whereas all organisms have this power. On the death of the organism the materials from which plants and animals are constructed pass back to the inorganic kingdom from whence they came; but the spark of life is potentially immortal, and is passed on by that most remarkable of all characteristics — the power which all living things have to reproduce their kind.

Plants and animals. The marked differences between plants and animals which can be easily discerned through a superficial observation of the higher types of each kingdom disappear when more lowly forms are studied. Nobody would ever mistake a cow for a cabbage, but there exist certain low forms of life which may with equally good reason be called plant or animal. In general the two may be contrasted in the following ways:

1. *Composition.* The green coloring matter of many plants is perhaps the most conspicuous feature of plants in general; yet certain plants (notably mushrooms and toadstools) are totally devoid of leaf green, and in this regard are similar to most animals. A few animals, on the other hand (notably protozoans, sponges, worms, and hydrozoans), possess the green coloring matter of plants. In like manner the cellulose, which constitutes the skeletal material of most plants, is generally absent in animals, although one group of animals (sea squirts) develop it abundantly in their bodies.

2. *Locomotion.* One ordinarily thinks of a plant as rooted to the ground and of an animal as a free motor organism. While this is generally true, there are noteworthy exceptions in some plants, which move about freely (diatoms), and some animals, which are attached throughout their adult stage of development (sea lilies, oysters).

3. *Response to stimulation.* Most plants react very slowly to any sort of stimulation, whereas most animals react definitely and quickly. Here, again, we find exceptions in the "sensitive plants," which react as positively as most animals, and in the sponges, which are as sluggish in regard to their response to stimulation as most plants.

4. *Growth.* The most fundamental difference between plants and animals lies in the type of food they consume. Plants live largely on carbon dioxide and other gases and liquids taken from the air, soil, and water about them. Having taken in these materials, the plants build them into starch, sugar, and other complex products through the agency of sunlight working on their green coloring matter. Animals, on the other hand, live not only on gaseous and liquid food but also on the solid material constructed in the bodies of plants. From this

point of view, animals are parasites on the plant kingdom, since they could not exist without the proteids, carbohydrates, and fats taken from plants. An exception to this rule is found in the fungi, which are colorless plants that live on organic matter, and in this regard resemble animals.

The nature of fossils. A *fossil* is the remains or the trace of the former existence of an organism, whether plant or animal, which has been buried by natural causes and preserved for a considerable time in the rocks of the earth's crust. In the past, only those organisms which have been buried in sedimentary materials soon after death, or have been incased by some substance that protected them from decay and the attack of living organisms, have been preserved as fossils. Most animals possess skeletal material composed of shell or bone; most plants have cellulose. The organisms which possess such hard parts are the ones most commonly preserved as fossils, although rarely organisms devoid of skeletal material leave a trace of their existence.

Unaltered remains of organisms. Very rarely an organism is preserved as a fossil with both hard and soft parts intact. Such were the specimens of the extinct mammoth unearthed in frozen gravels in Siberia. Not only were the bones and the hide preserved, but the flesh, which had been kept free from bacterial decay, was as sweet and fresh as the day the animal died. In like manner, a great many insects have been completely preserved by becoming embedded in fossil-tree resin (amber). Such resin is abundantly preserved in the Oligocene beds along the shores of the Baltic Sea.

Preservation with loss of soft parts only. It is quite common to find the shells and bones of animals preserved without change, long after the fleshy parts of the original organism have been dissolved and removed. Fossils of this type are very common, especially in the younger rocks.

Petrifactions. In many cases the original hard parts of an organism are partly or completely replaced by some foreign mineral substance. Such fossils, called *petrifactions*, are very common in all formations, but especially so in the older formations. Calcium carbonate and silica are the ordinary replacing minerals, although iron sulphide (pyrite) and carbon are not uncommon. The original material of the plant or the animal preserved by petrifaction may be but partly removed and replaced by mineral matter, or it may be entirely replaced. Even when the latter has taken place, the structure of the original substance may be preserved with the utmost fidelity. Petrifaction is usually accomplished by waters bearing mineral matter in solution and passing through rocks in which organisms have been buried.

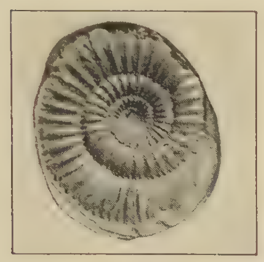

FIG. 182. The mold of a fossil shell

Molds and casts. If an animal or a plant falls on soft mud, it will leave an impression of its outline and surface markings. If for any reason the original organism is moved before burial takes place, the impression may remain and be buried and preserved without inclosure of the plant or animal that made it. Such an impression is called a *mold.* Some soft-bodied animals, such as jellyfish, have left fossil records of their former existence in molds. Because of their lack of hard parts they could be preserved in no other way.

In some cases a shell buried in the rocks may be completely removed by the solvent action of ground water. The cavity left behind may preserve the shape and the marking of the destroyed shell. If this cavity is filled with mineral matter at some later date, a *cast* of the original shell is the result. Such a cast would preserve the external characteristics of the organism, but the internal characteristics would, of course, be lost. Another type of cast might preserve the internal form of the shell but not the external. Still other types of molds and casts are produced, but the principle controlling their formation

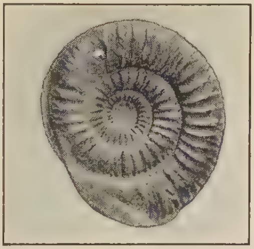

FIG. 183. A natural cast formed in the mold shown in Fig. 182

is similar to that in the types described. Molds and casts are common throughout the geological column, but especially so in the Paleozoic sedimentary rocks.

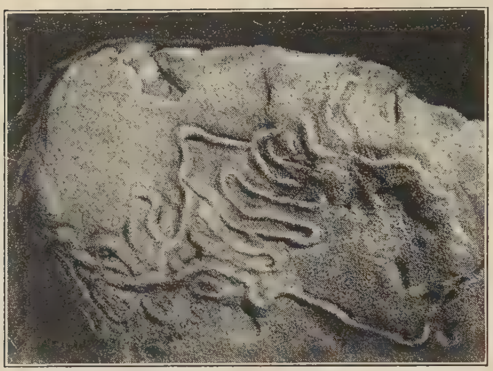

FIG. 184. A fossil worm burrow. (Specimen in Walker Museum, Chicago)

At one time the rock shown in this picture was sand on the shore of an ancient sea. A marine worm working through the sand left a tunnel to record its wanderings. Long afterward the sand was consolidated and cemented into sandstone, and the worm burrow was filled with a substance more resistant than the surrounding rock. As a result the burrow is preserved as a well-defined ridge rather than as a groove

Trails, tracks, burrows. *Trails* are the markings left by marine creatures on the soft sediments under the sea. Trails are often preserved as fossils when the sea bottom is elevated and converted into rock. *Tracks* are the impressions of the feet of land animals preserved in the tidal flats of the sea or on the flood plains of rivers. Such tracks, made by dinosaurs, abound in the Triassic rocks of the Connecticut valley. If the holes formed in soft earthy material by animals such as worms are filled up with sediment, under favorable conditions a tube of the filling material may be preserved as a fossil *burrow.* Worm burrows are the most common, and are known in rocks of all ages from the Proterozoic to the Recent. They indicate near-shore conditions, since most worms frequent the seashore.

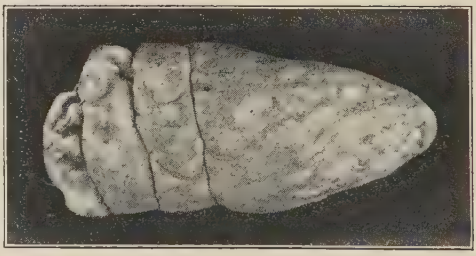

FIG. 185. The coprolite of a marine reptile from the Jurassic rocks of England. (Courtesy of the Field Museum of Natural History)

Coprolites. Masses of excrement from the intestines of extinct animals, particularly of fish and reptiles of Mesozoic age, are rather common. These masses are called *coprolites* and ordinarily are highly phosphatic. Coprolites sometimes throw light on the structure of the intestines and the nature of the food of ancient animals, but in most cases they are of little scientific value.

THE HIERARCHIES OF LIVING THINGS

All organisms can be placed in certain natural groups on the basis of general similarity in form, in activity, and in reproduction. The classification of living creatures lies within the province of the science of biology, so that only the great groups which have left a record of their past history as fossils in the rocks can be treated here, and these but briefly.

The Plant Kingdom

All the plants of the past and the present can be divided into four great groups. These in turn can be further subdivided, but we shall lay emphasis only on those members which are important geologically.

1. **Thallophyta.** The group of thallophytes includes all simple and primitive plants, in which there is no special division of labor for the purpose of performing the tasks necessary to the life of the organism. Thallophytes are composed of unorganized masses of plant tissue of irregular size and of variable shape, and are the lowest type of plants known.

The microscopic *bacteria* belong to this division. Although they consist of but a single cell, from the geological point of view they are undoubtedly the most important of all living things. They not only aided materially in the precipitation of limestone and certain sedimentary iron deposits, but were largely responsible for the decay of the vegetation which went into the making of the world's coal supply. Their present activity affecting the disease, death, and decay of higher organisms must have obtained throughout the past, so that their total influence was great, not only in supplying humic acid to the circulation of the ground water but also in destroying many organisms which might otherwise have been preserved as fossils. Related to the bacteria are the *blue-green algæ,* lowly one-celled plants always found in the presence of decaying organic material. Attention has recently been called to this group by the discovery of fossil blue-green algæ in rocks of Archeozoic age. These fossils are the oldest direct evidence of life thus far discovered.

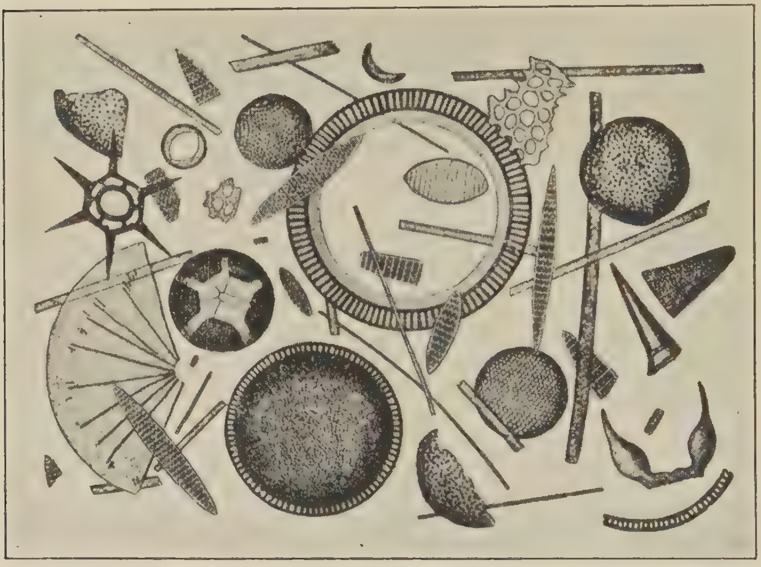

FIG. 186. Diatoms from the Antarctic diatom ooze. (× 300) (From Krümmel's "Oceanographie")

The *diatoms* are one-celled thallophytes which build an external skeleton of silica like spun glass (Fig. 186). Countless hordes of these tiny plants swarm in the sunlit surface waters of the present oceans. They are known in fresh water as well as in salt water, and are found even in marshy land. Their siliceous skeletons have often accumulated to great thicknesses in the past, and formations consisting almost entirely of diatom shells are known in the Mesozoic and Tertiary deposits of many regions, notably in California.

Various kinds of *algæ* (seaweeds) have preserved a record in the rocks. Modern algæ are classed as *green, brown,* and *red.* Among the green and red algæ are forms that secrete lime from the waters in which they dwell, and consequently are important rock-builders. A boring in the "coral" atoll of Funafuti showed a green alga to be the organism most abundantly represented and a red alga to be second in importance. Coral animals, ordinarily thought to be largely responsible for coral reefs, were but fourth in abundance. The same condition is thought to exist in many other modern coral reefs. In the past, calcareous algæ have been instrumental not only in the construction of reefs but in the production of certain limestones, in which the structure of the organism responsible for them has been destroyed by the leaching action of percolating waters.

2. **Bryophyta.** The bryophytes include a large number of simple plants, which are, however, of a distinctly higher type than the thallophytes. In the bryophytes we see a development from the water-living habits of most of the thallophytes to the land-living habits of most of the higher plants. We find in the bryophytes the development of special organs (roots, stem, and leaves) for extracting food from air and earth. In reproduction the bryophytes show themselves distinctly more advanced than the thallophytes. The adult bryophyte develops a capsule containing spores. When these spores are ripe, they fall to the ground and grow into a plant which gives rise to male and female reproductive organs bearing, respectively, the sperm and the egg cells. After the egg is fertilized by the sperm, the spore-bearing part of the plant develops. Such a change in the life history of an organism from a sexless to a sexed stage is called *alternation of generations.* In the typical bryophyte the spore-bearing stage always alternates with the stage wherein male and female elements are developed. No such complicated method of reproduction is known among the thallophytes; and for this reason, more than any other, the bryophytes are considered of a higher order. Bryo-

phytes, however, thrive best in moist soil. For this reason, as well as because some of their representatives are exceedingly primitive, they are perhaps more closely related to the water-dwelling thallophytes than to the pteridophytes.

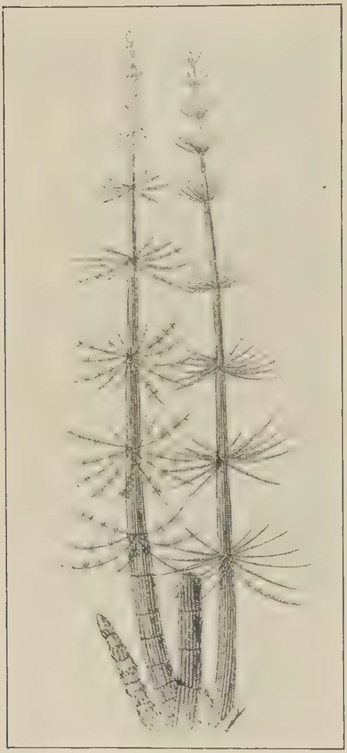

FIG. 187. Restoration of Calamites. (After Zittel)

Bryophytes are divided into *liverworts* and *mosses*. None of them secrete lime, so that their remains are rarely found in the rocks. The few fossils that are known were unearthed largely in the younger rocks of the earth's crust. Because of the primitive nature of this group it is likely that they existed during the earlier periods of geological time.

3. **Pteridophyta.** The plants of the third division represent a higher stage in the evolution of specialized organs than do the bryophytes. The tissues constituting the substance of pteridophytes are more like the higher flowering plants than are the more simple tissues of the bryophytes. Like the bryophytes the pteridophytes are spore-bearing plants and show an alternation of generations. The leafy stage in the life history of the pteridophytes is much better developed than that of the bryophytes, so that while the latter are small, inconspicuous growths, the former are prominent and in many cases large plants.

Ferns are pteridophytes which have peculiar interest for the student of earth history because they are among the most ancient of all land plants. The general appearance of ferns, with their broad fronds divided into several leaflets arranged along two sides of a stem, is familiar to all. Fossil ferns are known from the Devonian era to the Recent, and before the end of the Mesozoic most of the different types living on earth today had been evolved.

Horsetails (*scouring rushes*) are represented today by a low type of plant, the scouring rushes, which are usually small, with fluted and jointed stems. The leaves are small and inconspicuous and are grouped around the joints in the stems. Living horsetails, however, are but the sad survivors of a noble race of plants which in the past (especially during Pennsylvanian time) grew to treelike proportions and possessed large leaves. The best-known fossil horsetail is *Calamites*, which grew to the height of one hundred feet in the coal swamps of the late Paleozoic era (Fig. 187). The leaves of ancient horsetails are best known from a study of *Annularia*, which is associated with Calamites (some regard the specimens of Annularia as smaller branches of Calamites); the leaves of Annularia are bladelike and are united in a ring around the joints in the stem (Fig. 188).

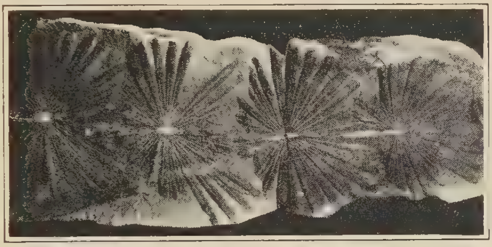

FIG. 188. Annularia. (Specimen in Walker Museum, Chicago)

Club mosses today are inconspicuous creepers in forests of the temperate zone, typified by the familiar ground pine. In the past, however, they were large and treelike and were very abundant in the swamps of the late Paleozoic. One of the most remarkable of the ancient club mosses was *Lepidodendron,* a lofty tree which in some instances attained a height of one hundred feet. The trunk was straight; near the top it forked, while each of the branches forked again, and so on. Such *dichotomous* division was typical of all lepidodendrons. The stems were covered closely with pointed leaves arranged in spirals. When the leaves were shed, peculiar scars were left on the stems (Fig. 189). *Sigillaria* was a tree very much like Lepidodendron, but had an unbranched stem, and leaves in vertical rows rather than in spirals around the stem (Fig. 190). Other and less striking club mosses are also known as fossils.

4. **Spermatophyta.** The spermatophytes include all the higher plants; namely, the plants which reproduce by means of seeds.

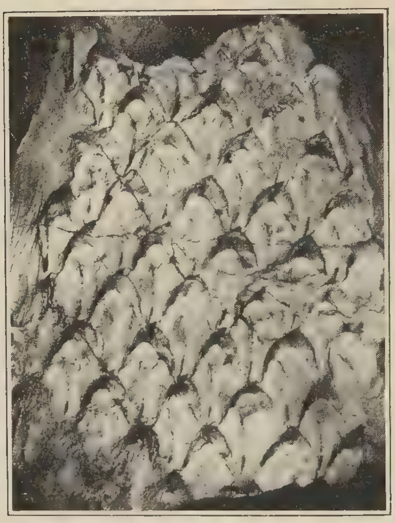

FIG. 189. Portion of the bark of Lepidodendron showing the leaf scars in diagonal rows across the trunk. (Specimen in Walker Museum, Chicago)

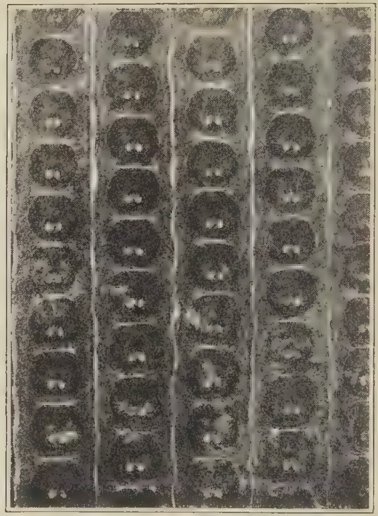

FIG. 190. Portion of the bark of Sigillaria showing the leaf scars arranged in vertical rows. (Specimen in Walker Museum, Chicago)

Two great subdivisions of the spermatophytes are recognized, known, respectively, as Gymnospermæ and Angiospermæ.

The *gymnosperms* ("naked-seed plants") are spermatophytes whose seeds are unprotected by any hard, resistant cover. Their principal representatives today are the needle-leaved evergreens.

An interesting group of plants with fernlike leaves developed during the Paleozoic and were long considered true ferns. Later, however, it was found that these forms reproduced not by spores but by seeds, and the name *pteridosperm* ("fernseed") was applied to them. They lacked an alternation of generations, but grew directly from the seed into sexed plants, and in so doing had taken the most important step forward known in plant evolution. The seed-bearing habit characterizes most plants today and is without doubt the best method of plant reproduction ever developed. Pteridosperms are known from the Devonian to the Jurassic period, but were not common after the close of the Paleozoic. *Neuropteris* and *Pecopteris* are the fernlike fronds of pteridosperms abundantly preserved in late Paleozoic sediments (Figs. 191 and 192).

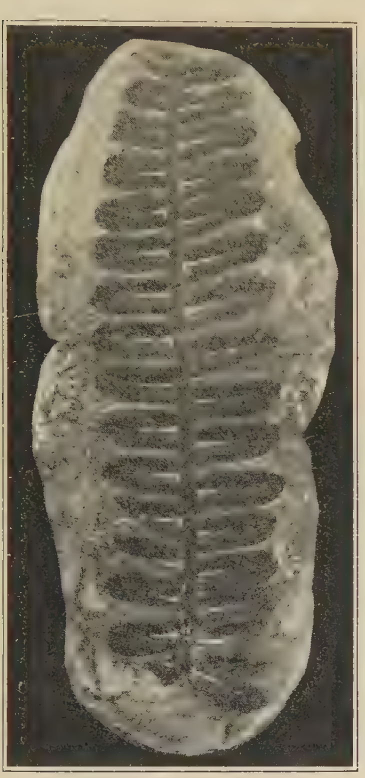

FIG. 191. Neuropteris. (Specimen in Walker Museum, Chicago)

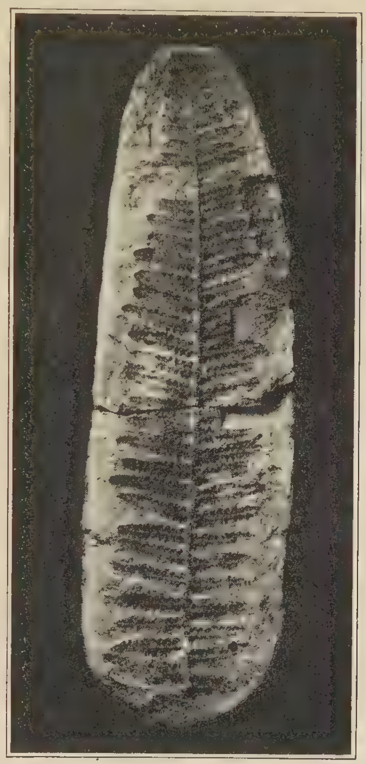

FIG. 192. Pecopteris. (Specimen in Walker Museum, Chicago)

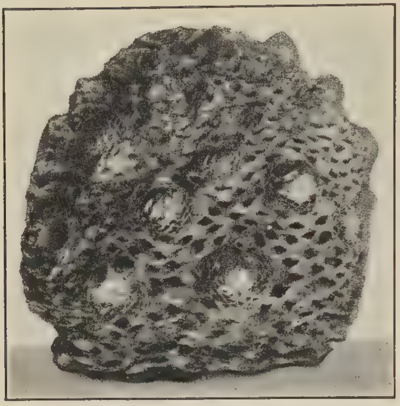

FIG. 193. A fossil cycad showing leaf pits. (Photograph by Professor T. H. Macbride)

The *cycads* are a group of gymnosperms which reached a high state of development in the early Mesozoic era and have persisted to the present in dwindling numbers, represented by the sago palms of tropical countries today. The stems of cycads are generally short and are thickly covered with leaf bases (Fig. 193). The crown bristles with large palmlike leaves. The cycads appear to have arisen from some pteridosperm, perhaps during the Devonian period. A close similarity exists between the fossil seeds of the two groups. Cycads are not common in formations older than the Triassic.

Certain trees not entirely unlike modern evergreens occur as fossils in the Paleozoic rocks. These were tall, slender trees with crowns composed of many bladelike leaves, some of which were several feet long. These trees, called *cordaites* (Fig. 194), did not bear cones, like most of our evergreens, but fruits more like that of the yew. The cordaites lived from Devonian to Permian time, when they became extinct.

The *ginkgoes* are an order of gymnosperms closely related to the cordaites. They are represented today by one species, the

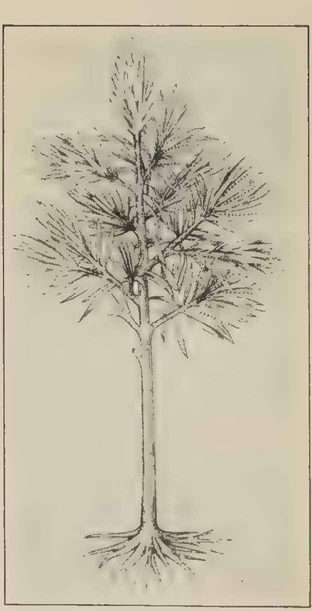

FIG. 194. Cordaites. (After Grand'Eury)

maidenhair tree of China and Japan. The ginkgoes had broad leaves, as compared with those of the cordaites, and branching trunks (Fig. 195). They are thought to have developed from the cordaites. By the Jurassic period they had spread all over the world.

Most of the living gymnosperms belong to a group known as the *conifers*, including yews, pines, cedars, junipers, and many related forms. These trees, except the yew family, bear cones, in which the seed lies bare between the front of one scale and the back of another. Most conifers are evergreen and possess small, stiff, needlelike or scalelike leaves. Their first record as fossils is in Permian strata, but they became increasingly common during Mesozoic and Cenozoic times.

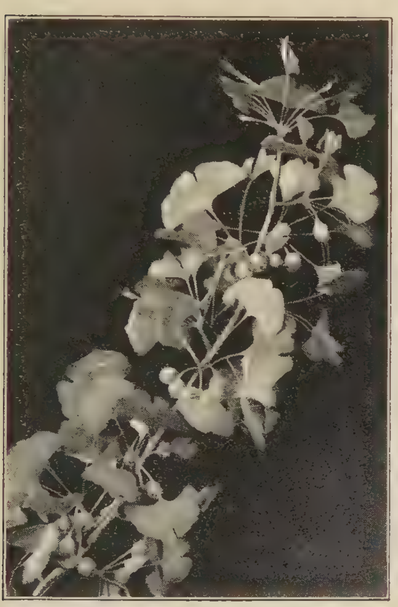

FIG. 195. Wax restoration of maidenhair tree, showing leaves and seeds. (Courtesy of the Field Museum)

FIG. 196. A fossil tree trunk, Montana. (Courtesy of the United States Forest Service)

The *angiosperms* ("cased-seed plants") represent the pinnacle of evolution in the plant kingdom. They are the prevailing type of plant on earth today, because they have proved themselves to be the most successful type. This division includes all plants bearing true flowers — not only many forest trees and flowering shrubs but also lesser flowering plants and grasses. Since angiosperms are the highest type of plant on earth, we should expect them to have been the last to appear. Such was indeed the case, since no undisputed angiosperm fossil is known from rocks older than the Lower Cretaceous.

CHRONOLOGICAL TABLE OF THE PLANT KINGDOM[1]

Spermatophytes	Angiosperms Gymnosperms	Lower Cretaceous to present Devonian to present
Pteridophytes	Club mosses Horsetails Ferns	Devonian to present Devonian to present Devonian to present
Bryophytes	Mosses Liverworts	Mississippian (?) to present Silurian (?) to present
Thallophytes	Seaweeds Diatoms Bacteria Blue-green algæ	Proterozoic to present Jurassic to present Proterozoic to present Archeozoic to present

THE ANIMAL KINGDOM

Like the plants, all animals fall into natural groups. Fifteen of such groups are recognized by biologists, although not all of these are represented in the rocks by fossils. The animal life of the past, as revealed by organisms possessing hard parts which made a fossil record of their existence possible, can be classified as follows:

1. **Protozoa.** The protozoans are the simplest of all animals, since they consist of but one cell of life jelly, which acts as a universal organ to perform all the tasks necessary to sustain life. They are mostly of microscopic size and are characterized throughout by the utmost simplicity. Food is ingested through the cell wall at any point and is digested in a cavity within the cell which acts as an improvised stomach and secretes an acid

[1] All terms have been Anglicized except where confusion might result.

solution that dissolves the particles of food material. The digested food is absorbed by the substance of the organism, and the indigestible waste material is eliminated at the most convenient point on the animal's body. Movement is ordinarily effected by the streaming of the entire substance of which the organism is composed into a projection which can be thrown out from any part of the body. Breathing takes place through the cell wall, oxygen being simply absorbed and carbon dioxide expelled. Reproduction is ordinarily effected by division: the cell body having grown to a certain size merely becomes constricted near the middle and then divides. Since it lacks mouth and digestive and excretory organs, or any specialized organs for moving, for breathing, or for reproducing, the protozoan is easily differentiated from all the higher animals. The protozoans are the only animals complete in one cell; and however simple the higher types may be, they are all multicellular and exhibit some sort of specialization of parts.

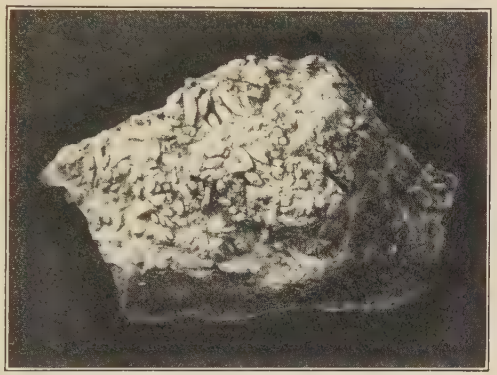

FIG. 197. A piece of limestone made up largely of the shells of Fusulina

The *Foraminifera* are protozoans which cover their bodies with a skeleton, usually of lime. They live largely in clear marine waters of shallow and intermediate depths. They are known in the rocks from the Ordovician to the Recent, but only occasionally did their skeletons accumulate to such an extent as to be of importance in rock-building. The Foraminifera first became conspicuous in Carboniferous time, when the spindle-like shells of *Fusulina* accumulated by the millions and formed limestones which cover extensive areas in North America, Europe, and Asia (Fig. 197). The widespread chalk formations in the Cretaceous systems of Europe and North America owe their existence largely to countless shells of Foraminifera. Great masses of limestone of Eocene age, several thousand feet in thickness, are full of the skeletons of *Nummulites* (Fig. 198). These so-called *nummulitic limestones* occur in the countries bordering the Mediterranean Sea, and in Japan, the East Indies, and Central America. The shell of *Nummulites* is disk-like and is composed of many chambers. Because of their relatively convenient size (ordinarily from a quarter of an inch to one and one-half inches across) and their flat, round shape, nummulite shells were used by earlier civilizations as a medium of exchange. The present fashion in the shape of coins probably owes its origin to these fossil shells.

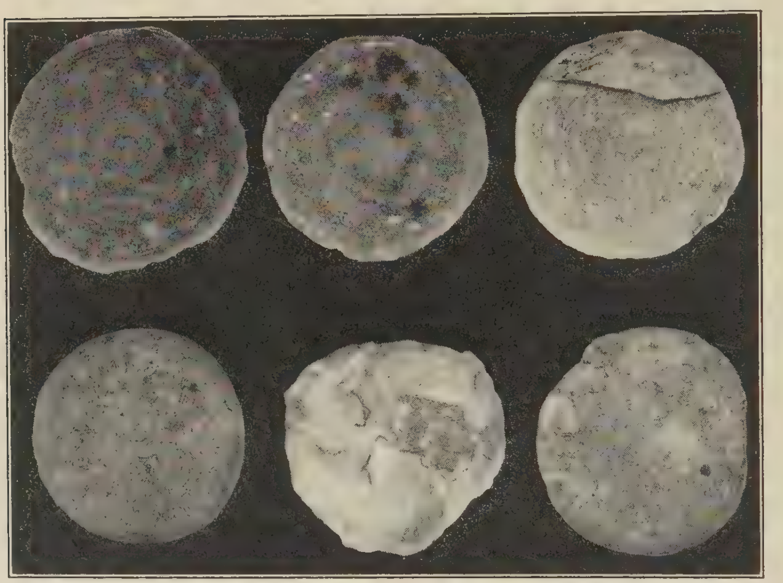

FIG. 198. Tertiary Nummulites, Egypt. (Courtesy of the Field Museum of Natural History)

The *Radiolaria* are protozoans which secrete a glassy rather than a limy skeleton. They possess exquisite shells, which are ordinarily built on the plan of a star, with a central disk and radiating "points" (Fig. 199). Like the Foraminifera, these siliceous organisms live in marine waters, and on death their skeletons fall to the bottom to form an ooze. Because of the resistance of their glassy shells, well-preserved radiolarians have been discovered at great depths. Although most Radiolaria and Foraminifera live near the surface of the sea, the limy skeletons of the latter are dissolved before they can sink to any great depth. Radiolaria are known in the rocks from the pre-Cambrian to the present. They became important rock-builders during Tertiary times, when the famous Barbados earth, made up entirely of the siliceous skeletons of radiolarians, was accumulated.

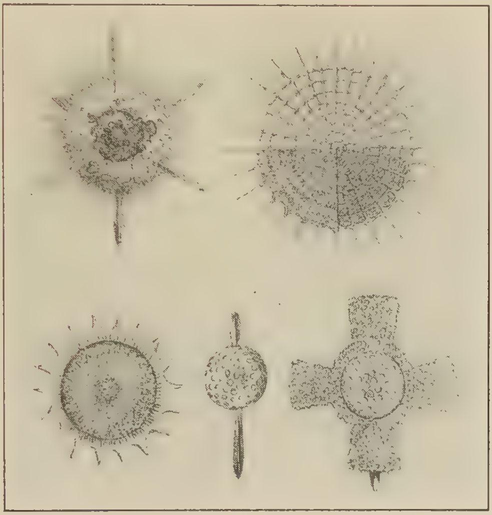

FIG. 199. Tertiary and Recent radiolarians. Highly magnified. (After Zittel)

2. **Porifera.** An advance over the protozoans is shown by the sponges (Porifera), which possess bodies of many cells. They live attached to the sea bottom, usually in colonies. A few are known to inhabit fresh water. Many shapes are found in the sponges, from simple globular forms to urn-shaped and club-shaped varieties. Sponges are hollow within and open at one end. Water passes into the central cavity through pores in the wall, carrying food material which is absorbed by the animal through the agency of cells specialized for this purpose. The water then passes out through the opening at the unattached end of the organism, carrying all waste material with it. Reproduction is effected by special male and female cells. The skeleton consists of calcareous or

siliceous *spicules* secreted in the body of the animal. Some sponges have skeletons of horny material. It is from this variety that the familiar bathroom sponges come. Nearly all fossil sponges belong to types which possess limy or glassy hard parts. Most sponges are so loosely put together that on death their skeletons fall apart, and only an occasional rodlike spicule is preserved. A few sponge colonies, however, with spicules firmly reticulated, have been preserved in their entirety (Fig. 200).

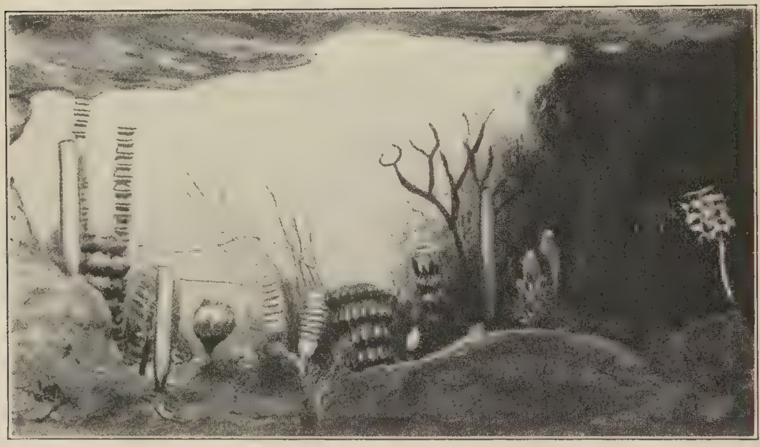

FIG. 200. Restoration of siliceous sponges from the Devonian strata of New York. (Published by permission of the New York State Museum)

Sponges constitute a small but distinct group of animals. They are sluggish and plantlike in many of their habits. They are known in the rocks from the Proterozoic to the present. Flint nodules in limestone often show the presence of sponge spicules. Such nodules are common in the great chalk deposits of the Cretaceous as well as in some older limestones, notably those of Silurian age in the vicinity of Chicago. With a few local exceptions, complete fossil sponges are rare.

3. **Cœlenterata.** The cœlenterates are represented by the living jellyfish, sea anemones, and corals. Such animals are more highly organized than the sponges in possessing a mouth, surrounded by tentacles, which opens into a digestive cavity,

and in having three distinct layers of cells in the body wall. The cœlenterates are characterized by specialized nettle cells not found in any other organisms. When the animal is irritated, it shoots out hundreds of these filamentous cells and stings its enemy to death. The great Portuguese man-of-war has tentacles several feet long, and nettle cells powerful enough to throw a man into spasms. Cœlenterates reproduce by means of specialized sex cells as well as by the process of budding.

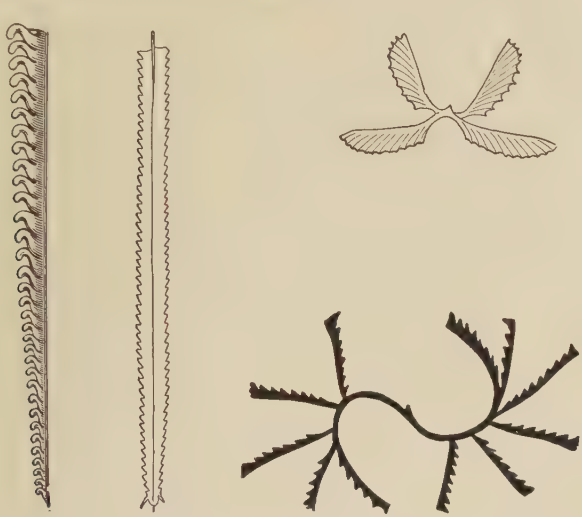

FIG. 201. Graptolites. (By courtesy of W. H. Norton)

The *graptolites* are an extinct order of cœlenterates of great importance to the geologist. They lived in colonies, either attached to the sea bottom or floating on the surface of the water. They all secreted horny skeletons composed of many little cups arranged along a medial rod (Fig. 201). In each cup lived the individual graptolite animal. The impression of a graptolite colony on a rock resembles ancient inscriptions on stone, and for this reason the graptolite ("written stone") received its name. Graptolites are first known in rocks of Upper Cambrian age. Their greatest development took place in the Ordovician period, although they were not uncommon in the Silurian as well. Only a few were left by Devonian time, and the last of the race perished with the Mississippian. Because many of these creatures had the habit of living on the surface of the sea, their remains were scattered all over the world by currents during the Ordovician period. Their impressions, which are most common in shale rock, have in several cases acted as valuable horizon-markers in the correlation of widely separated formations. Some graptolites encircled the globe in a comparatively short time, so that where their remains are preserved the rocks containing them must have been deposited contemporaneously.

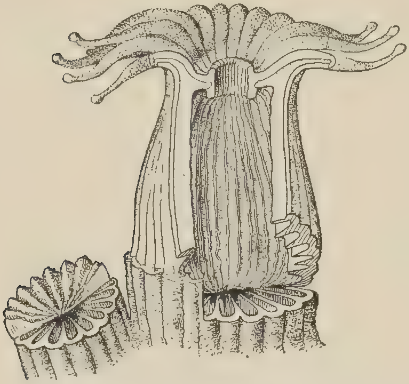

FIG. 202. Diagram of a coral animal with part of the wall removed to show the relation of the soft-bodied polyp above and the stony skeleton below

Related to the graptolites are the *jellyfish*. These are free-swimming, umbrella-shaped animals that are known to have existed from the Cambrian period. Their preservation is remarkable, as they are devoid of hard parts and as about 99 per cent of their substance is water. But their impressions on the fine muds of several ancient sea bottoms remain to record their existence; particularly fine specimens have been discovered in the lithographic stone quarries of Solnhofen, Bavaria (Jurassic).

Corals are the most abundant of all cœlenterates, both living and fossil. They are more highly developed than the graptolites and jellyfish, inasmuch as their body walls are modified by a system of longitudinal partitions which stand out into the interior cavity. The typical coral has the power of secreting lime in the cells of the outer layer of its body. Normally only the base of the coral animal secretes lime; as growth takes place the animal, which lives on top of its skeleton, is raised higher and higher, and more and more of the skeletal rock accumulates below. In this way corals have acted as important rock-builders (Fig. 202). Coral-like animals are known from the Proterozoic; but true corals have not been found in rocks older than the Ordovician, whence they continue in more or less abundance to the present. Most corals were restricted to clear, warm marine waters. They are found largely in limestone rock and occur both singly and in colonies. Great reefs of extinct corals are known in several localities, the most noteworthy being the Devonian coral reef at Louisville, Kentucky.

Most of the cœlenterates, and especially many of the corals, possess bodies which radiate from a central axis. If such an animal is cut into two parts along a plane passed through the central axis, the parts are seen to be identical. No matter where the animal is cut, as long as the plane of division passes through the central axis the two halves will be similar. Such an animal is said to be *symmetrical* in regard to the two sides of the plane of division. Since planes of this sort may radiate in all directions from the central axis, like the spokes of a wheel, the symmetry is called *radial*. Radial symmetry is the most simple type and is possessed largely by such animals as are rooted to the ground during the adult stages of growth. Most of the successful animals of today have abandoned radial symmetry for a higher type of symmetry, discussed under the following group.

4. **Vermes (worms).** Modern science divides the worms into four great groups, exemplified by the living types known as flatworms, threadworms, wheel worms, and segmented worms. Only the last group has left any undoubted trace in the sediments of the past. The old term *Vermes* formerly served to include all soft, wormlike animals lacking a backbone. We use it here to include all types of worms, because these creatures are so rare as fossils that for our purpose they can be treated en masse.

The segmented worms (*annelids*) are the highest type of worms and mark a distinct advance over the cœlenterates. They are generally characterized by a long body divided into segments, with a mouth at one end and an anus for the expulsion of waste material at the other. They are the simplest organisms possessing a differentiated nervous system and specialized organs for digesting and excreting waste material. They possess also a heart. Some segmented worms have bristles (sea worms); others are devoid of bristles (leeches). Bristled annelids (chætopods) are known from the Cambrian to the present, and burrows, which are attributed to some sort of worm, are known in pre-Cambrian rocks. Small jaws, thought to have belonged to annelid worms, are known from Middle Paleozoic formations. With the exception of such small fossils, the geological record of worms consists largely of burrows, and these yield but little information concerning the creatures which made them.

If an imaginary plane is passed through the middle of a man's body from front to back and from the head to the crotch, the two parts of the body are seen to be mirror images of each other. Man's body is therefore symmetrical with regard to the two sides of the imaginary plane. Such symmetry is known as *bilateral* and is characteristic of all higher animals. The body of a worm can be divided along its length into two parts which are mirror images of each other; therefore it can be said to be bilaterally symmetrical. Animals possessing such symmetry have their important organs arranged in pairs on each side of the plane of symmetry, just as the eyes, ears, legs, and arms of a man are arranged. Since there is only one plane through which a bilaterally symmetrical animal can be divided into two similar parts, such an animal possesses not only a *right* and a *left* side which are mirror images, but also a *top* and *bottom* which are distinctly different. In the case of man, who walks erect, the top becomes the *back* and the *bottom* becomes the *front*. Worms are the lowest organisms possessing bilateral symmetry, — a symmetry which characterizes all the back-boned animals and many of the more successful animals lacking a backbone.

5. **Echinodermata.** The group of echinoderms contains a great variety of spiny-skinned marine animals, typified by the

familiar starfish and sea urchin of modern seacoasts. Like the annelids, they possess a digestive tube which is distinct from the body cavity, a nervous system, and an exclusively sexual method of reproduction. The skeleton consists of many calcareous plates embedded in the skin of the organism. These plates are often surmounted by spines, and from this characteristic the group received its name *Echinodermata* ("hedgehog skin"). The most striking feature of these animals is the pronounced radial symmetry possessed by most of them. They are built on the plan of a wheel with hub and spokes. The spokes, consisting of rows of skeletal plates, are characteristically developed in fives or multiples of five, so that the symmetry is said to be *pentamerous*. Despite their primitive radial symmetry, echinoderms show an advance over all animals discussed thus far in that they possess highly developed organs of locomotion consisting of many tiny tube feet which are made to expand and contract as water is forced in and out. When the tube feet are made to expand in the direction of movement, and come in contact with the rocks on the sea bottom, they are held firmly rooted by a partial vacuum which develops at the base of each tube foot when the water is expelled from them. Contraction of the tubes follows, and the animal is pulled ahead. Some echinoderms are rooted to the ground by a stem during the adult period of life; others, such as the starfish, are unattached and free-moving types throughout life. None are colonial.

The *cystoids* are the most primitive echinoderms. They reached the culmination of their development during the Ordovician and the Silurian period, although they are known throughout the Paleozoic from the Cambrian to the Permian. Their name, which means "bladderlike," refers to their globular shape. They differ from all other echinoderms in that the plates of their bodies are not arranged in any regular pattern. They are attached to the bottom by a stem composed of hollow, ringlike plates (Fig. 203).

The *crinoids*, or "sea lilies," were probably evolved from the cystoids. The crinoids, like the cystoids, are fixed to the ground during the adult stage, but the plates of their skeletons are regularly arranged. They are ordinarily surmounted by branching arms, which are used to conduct food into the mouth, and which give the animals their plantlike appearance. Their name, *crinoid*, which means "like a lily," refers to their characteristic form. Crinoids reached their maximum development during the Mississippian, although they were also abundant in the Silurian and Devonian seas. They are first known from the Ordovician and have persisted into the present on a much reduced scale. Some Paleozoic limestones (crinoidal limestones) are almost entirely made up of the broken fragments of the stem and body plates of crinoids.

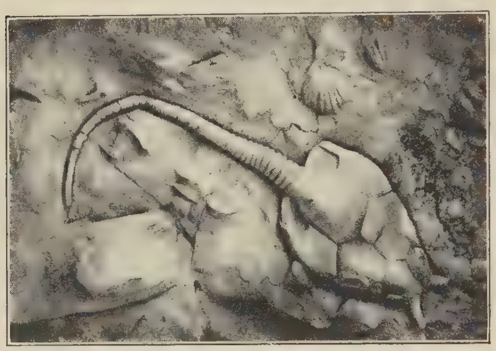

FIG. 203. A cystoid showing stem and arms. (Specimen in Walker Museum, Chicago)

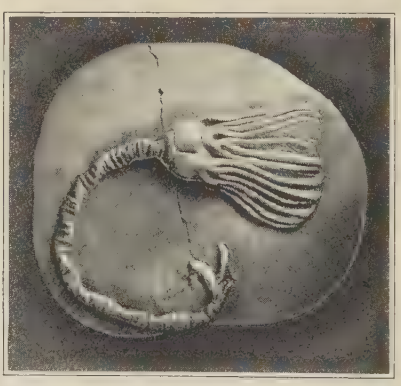

FIG. 204. A fossil crinoid, with arms, stem, and "anchor" preserved. (Specimen in Walker Museum, Chicago)

The *blastoids* are the third member of the triumvirate of simple echinoderms. Their stems are short or lacking; their arms are rudimentary. They are globular, and are known as blastoids ("like a bud") because of their bud-shaped bodies (Fig. 205). The skeletons of typical blastoids always consist of thirteen definitely arranged plates. One type is exceedingly abundant in Upper Mississippian limestones. Like the cystoids, the blastoids are restricted to the Paleozoic, and range from the Ordovician to the Permian. They were not plentiful until the Carboniferous.

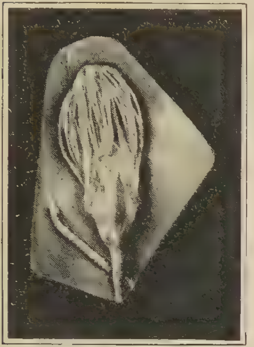

FIG. 205. Blastoid showing well-preserved arms. (Specimen in the Walker Museum, Chicago)

The *asteroids*, or *starfishes*, are the most simple of the freely moving echinoderms. They are known from the Cambrian to the present, but are extremely rare as fossils (Fig. 206). As their name ("starlike") indicates, their bodies are star-shaped. It is interesting to note that the early Paleozoic starfishes are very similar to those living today. Their evolution took place very early in the Paleozoic, and little change has been effected since. Related to the starfishes are the *ophiuroids*, or *brittle stars*, in which the central disk is sharply separated from the arms and contains all the vital organs (Fig. 207). Brittle stars are known from the Ordovician to the present, but are far more common today than during the past.

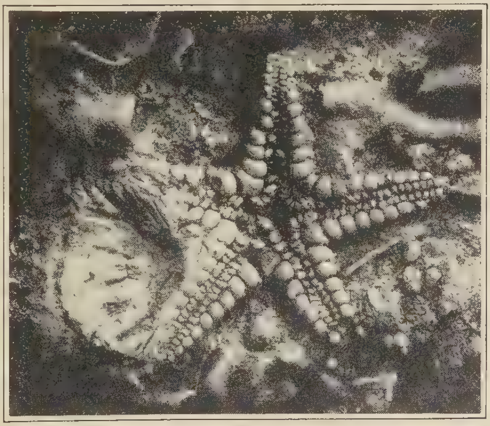

FIG. 206. A fossil starfish. (Specimen in Walker Museum, Chicago)

The echinoids (*sea urchins*) are the most highly developed of all the echinoderms. Like the starfishes, they are freely moving types. The skeleton is globular, and a complicated organ for masticating food is present. They are usually covered with a thick carpet of spines, as their name implies. They move either by tube feet, like the starfishes, or by vibrating their spines. Unlike the attached echinoderms, whose mouths are on the upper surface, the freely moving echinoderms have mouths on the under surface. Sea urchins are known from the Ordovician to the present, although they are not abundant as fossils until the Mesozoic (Fig. 208).

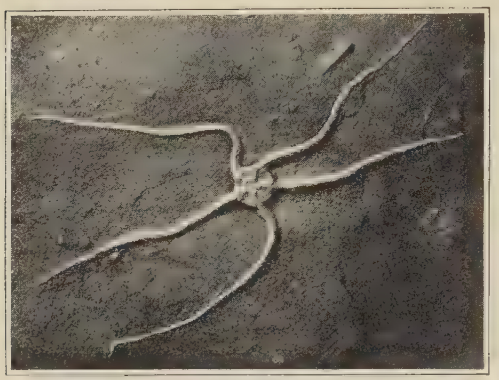

FIG. 207. A fossil brittle star. (Specimen in Walker Museum, Chicago)

The *holothurians,* or *sea cucumbers,* are a group of echinoderms which show a marked tendency away from the radial symmetry that characterizes the Echinodermata as a whole. Other forms, notably some of the crinoids and echinoids, show the beginning of a bilateral symmetry, but not in such a marked degree as do the holothurians. These animals are drawn out along an axis which extends from the mouth at one end to the anus at the other. They possess a comparatively soft body, only slightly supported by calcareous plates, and are exceedingly rare as fossils, although they are known from the middle Cambrian to the present. They are very abundant in present oceans.

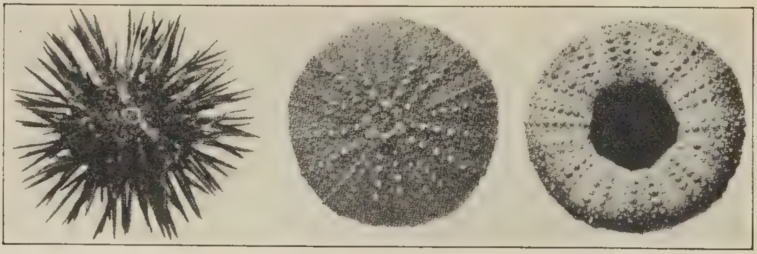

FIG. 208. Living sea urchins. (Reprinted by permission from "Textbook of Geology," by L. V. Pirsson and Charles Schuchert. Published by John Wiley & Sons, Inc.)

6. **Molluscoidea.** Molluscoidea are mostly sea dwellers. They are more advanced than the echinoderms, inasmuch as they all show pronounced bilateral symmetry and a well-developed digestive canal. They were originally classed with the mollusks, because of certain superficial similarities, but are now known to form a distinct group. Their name, however, which means "mollusk-like," refers to these superficial similarities.

The *bryozoans*, or *moss animals*, are the more simple of the two great subdivisions of the Molluscoidea. The individual bryozoan animal is very small, and in only a few cases lives alone. These organisms are usually colonial in habit; and since they often live attached to rocks and shells, forming over such objects an encrusted layer very similar to moss on a stone, they are called bryozoans ("moss animals"). The organism has a mouth surrounded by a ring of tentacles, a U-shaped digestive tube, and a body wall which secretes a horny or calcareous skeleton. The bryozoans are known from the Ordovician to the present. In the Ordovician they lived in great massive colonies which were of no slight importance as rock-builders. The reefs of the Ordovician seas were largely composed of such bryozoans. Not until later in the Paleozoic did the corals develop to such a degree as to supplant the bryozoans as reef-builders. As the Paleozoic advanced, massive bryozoans grew less abundant, and delicate, lacelike colonies took their place (Fig. 209). By the close of the Paleozoic most bryozoans were of the delicate kind, and many forms had developed a variety of supporting structures to strengthen the colonial skeleton against the beating of the waves.

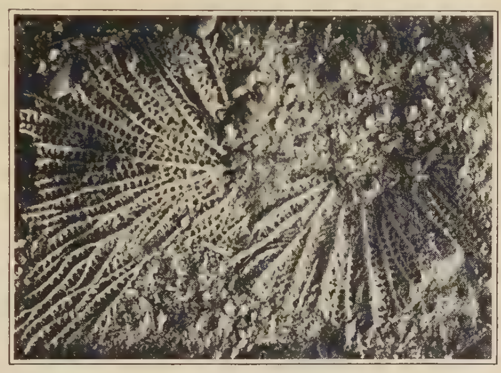

FIG. 209. A late-Paleozoic bryozoan colony. (Specimen in Walker Museum, Chicago)

The *brachiopods* secrete a shell composed of two valves, of which ordinarily one is larger than the other. If a plane is passed through the middle of a brachiopod shell, cutting both valves, the two parts will be mirror images. In this regard the brachiopod shells differ from the shells of clams and related forms. Clams, like brachiopods, have shells consisting of two valves; but the valves of a clamshell are ordinarily of the same size and are mirror images of each other, just as are the two hands of a man. Thus the plane of symmetry in the clam passes *between* the two valves; in the brachiopod it cuts *through* the middle of both valves (Fig. 210). Brachiopod shells are therefore situated on the *back* and *belly* of the animal, whereas clamshells cover the *right* and *left* sides.

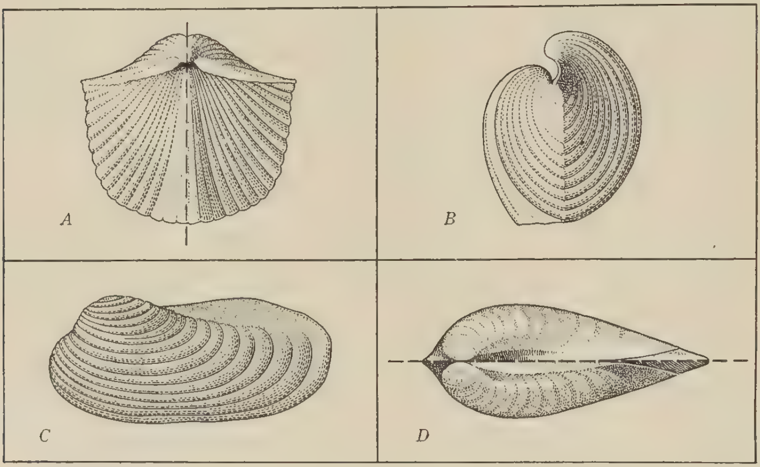

FIG. 210. Diagram illustrating the different symmetry of brachiopods and pelecypods

A, brachiopod with plane of bilateral symmetry passing through the middle of the valves; *B*, brachiopod showing the inequality in the size of the valves; *C*, pelecypod showing the inequilateral shell; *D*, pelecypod with plane of bilateral symmetry passing between the valves

During life the brachiopod shells lie flat on the sea bottom, and the animal attaches itself to a foreign object by means of a fleshy projection (pedicle). The valves are often ornamented with rib-like markings, and in most cases are held together by some system of tooth-and-socket joints at the attached end. Inside the shell is the soft body of the animal, inclosed in a skinlike mantle. Brachiopods have a well-developed digestive tract, heart, separate male and female sex organs, and muscles for opening and closing the valves. Two spiral "arms" occupy the anterior part of the shell and function as organs of breathing. From these the brachiopod ("arm-foot") receives its name. The so-called arms were originally thought to be organs of locomotion. Some modern brachiopods resemble a small Roman lamp, and for that reason the group is sometimes referred to as the "lamp shells," although ancient brachiopods only rarely show this similarity.

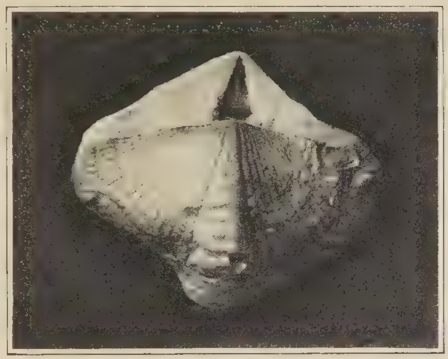

FIG. 211. A large Mississippian brachiopod. (Specimen in Walker Museum, Chicago)

The brachiopod shell may consist of lime carbonate, lime phosphate, or a horny substance. These animals existed from the Cambrian to the present, and were the most common of all organisms during the Paleozoic. Most of the earlier brachiopods were simple and had horny shells, possessing no organs of articulation other than the muscles of the animal's body. By Ordovician time the lime-secreting habit had become well established, and more advanced types of brachiopods came into being. By the Devonian the brachiopods had reached their climax and swarmed in the warm ocean waters of all lands. They were still abundant in the Mississippian period, but suffered a decline with the advent of the Mesozoic era, from which time they have persisted in diminishing numbers to the present. Some species lived for but a relatively short time, yet during that time became widely distributed. Such species as these are valuable indicators of the relative age of various rock formations. Other brachiopods were remarkably persistent, and a few types have lived almost unchanged from the early Paleozoic to the present.

7. **Mollusca.** The great group of mollusks includes the familiar clam, the snail, and the devilfish. The group name, which means a "soft-bodied animal," has little special application to the animals included under it. With the exception of the snails, mollusks are bilaterally symmetrical animals. Most of them secrete limy shells. They inhabit both fresh and salt water, as well as land. Many subdivisions of Mollusca have been distinguished, and over sixty thousand species of these creatures are already known.

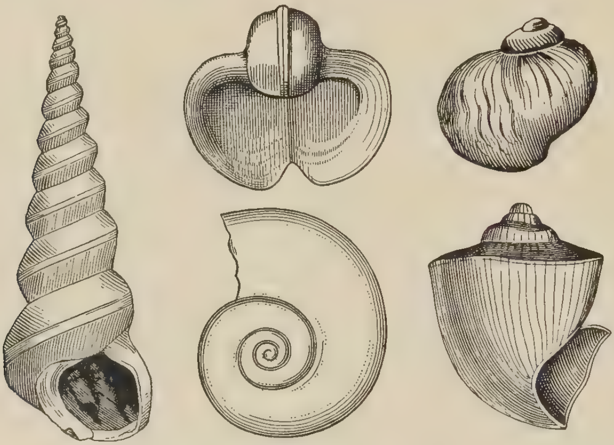

FIG. 212. Fossil gastropods. (Courtesy of W. H. Norton)

The *gastropods* are the snails, animals that possess a distinct head (in most cases with eyes and tentacles), a muscular foot for locomotion, and a fleshy mantle which incloses the viscera. They secrete a spiral, usually turreted shell. The digestive, circulatory, and nervous systems are more specialized than are those of the brachiopods, but the greatest advance shown by this group is in the well-defined head and the fleshy foot. The close relationship of the foot and the stomach in the body of these animals gave the group its name, which means "stomach-foot." Gastropods are first known in the Lower Cambrian, and have slowly developed from simple, primitive types to more complex types. Their advance has been steady, suffering no marked reversals and enjoying no sudden advances. They are more abundant, more varied, and more highly developed today than ever before (Fig. 212).

The *pelecypods* are the clams, oysters, and related forms. They secrete a calcareous shell consisting of two valves (see page 306). Pelecypods have a fleshy foot by which they burrow into the sand and mud, but they lack any distinct head. The valves are held together by a hinge and can be opened or shut by means of a ligament and muscles. The pelecypods breathe with gills, and they have specialized organs for admitting and rejecting water. They have also special organs for pumping their colorless blood and for digesting food and eliminating waste. The nervous system is simple, but it is more advanced than that of the brachiopods and bryozoans. The term *pelecypod* ("ax-foot") refers to the shape of the organ of locomotion (Fig. 213).

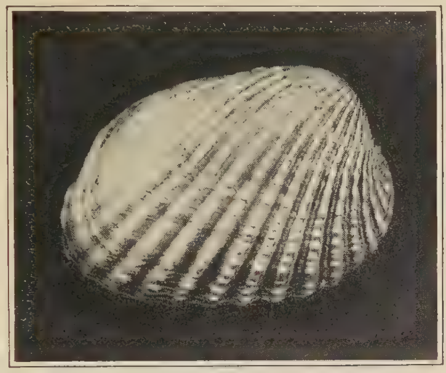

FIG. 213. A fossil pelecypod

The first fossil remains of undoubted pelecypods are known from the Ordovician. From their first appearance to the present no striking changes in the habit or aspect of these creatures have taken place. It is true that whole races of pelecypods have come, disappeared, and been supplanted by new types; and yet no spectacular developments have characterized the group throughout their long history. They are the symbol of conservatism in nature.

The *cephalopods* mark the culmination of molluscan evolution. They are typified by the living pearly nautilus, the squid, and the devilfish. Since in these animals the head and the foot are combined, they are called cephalopods ("head-foot"). Some cephalopods have an external shell, others have an internal shell, and a few have no shell whatsoever.

Of the large group of cephalopods which dominated the seas of the early middle Paleozoic, only the pearly nautilus survives. These ancient cephalopods were quite different from most modern forms in that they possessed an external skeleton of many chambers, the last of which was tenanted by the soft body of the animal. They had a head with eyes, tactile and sucking organs, four gills, and four kidneys. They fall naturally into two great groups: the nautiloids and the ammonoids.

The *nautiloids* have straight, bent, curved, or coiled shells. The transverse partitions (*septa*) which divide the shell into chambers are simple and join the outer shell in straight or undulating lines (*sutures*) (Fig. 214). A fleshy extension (*siphon*) of the body passes back from near the center of the living chamber to the chambers occupied successively during the earlier stages in the life history of the organism. The siphon secretes a calcareous wall about itself (*siphuncle*), and thus permanent communication is established between the living chamber and the chambers which formerly housed the organism. The purpose of the siphon is unknown, although it seems likely that by means of it the animal inflates the unoccupied portions of its shells with air and thus renders its entire body more mobile. In the nautiloids the siphuncle is always either central or near the inner margin of the shell. The evolution of the nautiloids progressed from the simple, straight shells through the bent, curved, and coiled types. They are first known in the Cambrian and reached their climax in the Silurian, when over a thousand species existed. From this point their decline was rapid until at present Nautilus alone is left. Some of the straight-shelled nautiloids reached a length of as much as ten or fifteen feet, and were undoubtedly the largest and most powerful animals in the lower middle Paleozoic seas until the fishes rose to supremacy over them.

The *ammonoids* were an outgrowth from the nautiloids. They differed from the latter in having sutures that were more complicated and in having siphuncles situated near the outer margin of the shell (Fig. 214). They are known first from the Silurian. During the Mesozoic they rose to a great climax, but

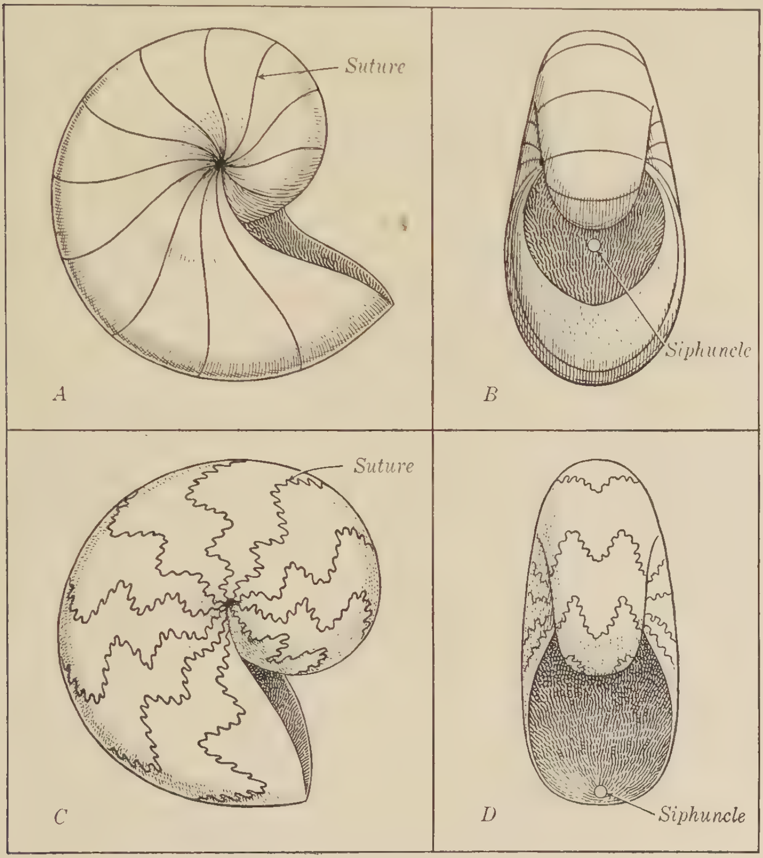

FIG. 214. Diagram illustrating the chief characteristics of nautiloids and ammonoids

A, nautiloid showing the simplicity of the sutures; *B*, nautiloid with siphuncle emerging near the center of the living chamber; *C*, ammonoid showing the complexity of the sutures; *D*, ammonoid with siphuncle emerging near the margin of the shell were entirely wiped out at the end of that era. Some had beautifully ornamented shells, which in most cases were tightly coiled.

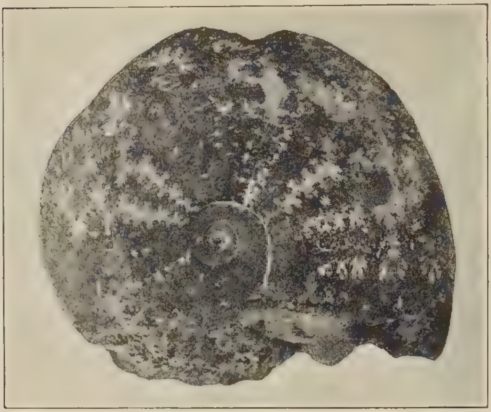

FIG. 215. A Jurassic ammonoid showing the complexity of the sutures. (Courtesy of the Field Museum of Natural History)

Modern cephalopods are distinguished by a nonchambered shell (which in most cases is internal), a well-developed head with mouth, eyes, and sucking tentacles, and an ink sac that can be made to discharge a dark fluid which hides and protects the animal when it is startled. This group is composed of the squids and their extinct allies, possessing ten tentacles, and the octopuses, with eight tentacles. They are known from the Triassic to the present. The fossil *Belemnites* (Fig. 216) was an organism closely resembling the modern squids. It lived in great abundance during the Jurassic and the Cretaceous, but became extinct at the end of the Mesozoic.

8. **Arthropoda.** The Arthropoda are numerically the greatest subdivision of the animal kingdom. They are represented by lobsters, crabs, centipedes, and the ubiquitous insects. These animals are all characterized by a horny skeleton which covers the outside of the body and is transversely divided into segments. The organisms are bilaterally symmetrical, with elongated bodies possessing a mouth at one end and an anus at the other. The nervous system is complicated and lies along the under side of the body. Normally each segment of the

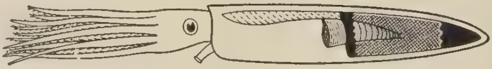

FIG. 216. Belemnites, the forerunner of the squid
Hard parts preserved as fossils are shaded

arthropod body has a pair of appendages which are jointed and give the name *arthropod* ("joint-foot") to the group. Eyes are nearly always present, and the digestive and circulatory systems show an advance over those of all the organisms previously mentioned. Arthropods grow by periodically shedding their horny skeletons until maturity is reached. The sloughed shells of a single individual may be preserved, so that not one but many fossils of the animal are left to render an account of its existence. This group was probably evolved from some annelid worm, and several main branches developed and adapted themselves to the water, the land, and the air.

The *Crustacea* are the most primitive arthropods. They are all water-living types and breathe by means of gills. The familiar crabs and lobsters are typical crustaceans. During the Paleozoic a great race of crustaceans, the *trilobites*, were among the most abundant and most interesting creatures that peopled the warm, shallow seas. A three-part division, which is responsible for the name *trilobite* ("three-lobed"), is imparted by two furrows running the length of the animal's body (Fig. 217). Trilobites ranged in size from tiny individuals a third of an inch long to giants of over two feet in length. These creatures are always found in shallow-water marine sediments and are associated with brachiopods, corals, echinoderms, and similar organisms. They are the most characteristic fossils of the Paleozoic rocks, beginning in the Lower Cambrian and becoming extinct in the Permian. They were very abundant during Cambrian and Ordovician times, but began to decline in the Silurian. As their racial vitality ebbed, picturesque bizarre forms were developed, possessing many

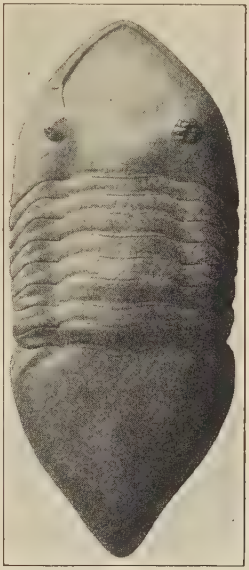

FIG. 217. An Ordovician trilobite. (Specimen in Walker Museum, University of Chicago)

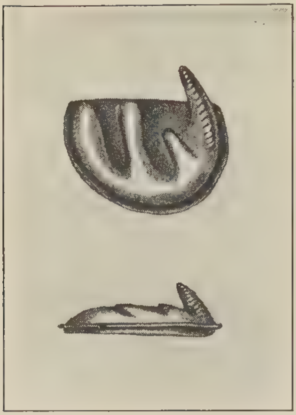

FIG. 218. Views of a fossil ostracod, magnified

spines and pustules. During the early Paleozoic the trilobites were the chief meat-eating organisms of the period and consequently dominated the life of the seas. Later, however, with the rise of the cephalopods and fishes, the death knell of the trilobite was sounded, since it could not compete with such powerful and active animals.

Besides the trilobites several other kinds of crustaceans are known as fossils. Minute, unsegmented, bivalve types (ostracods) are abundant in all rocks from the Ordovician to the present (Fig. 218). The crab-like and shrimp-like forms do not become common until the Jurassic period (Fig. 219).

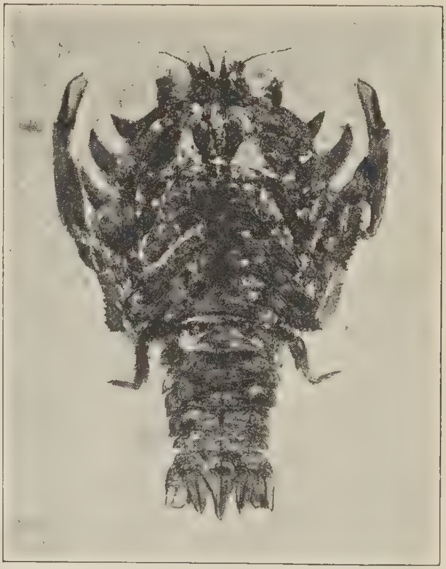

FIG. 219. A Jurassic crab from Solnhofen, Bavaria. (Courtesy of the Field Museum of Natural History)

The *Arachnida* (spiders etc.) contain both water-breathing and air-breathing types. Most of them are characterized by four pairs of legs. The *eurypterids* are an extinct order of sea scorpions belonging to this group. They are characterized by a pair of very much enlarged winglike legs (Fig. 220). They lived throughout the Paleozoic era, and are important because from them were developed the land scorpions, the first air-breathing animals to leave the sea and inhabit the lands. This evolution probably took place along the shore lines of the Silurian sea in northwestern Europe.

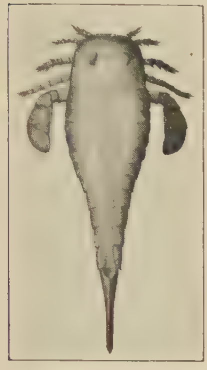

FIG. 220. A eurypterid

The *Myriapoda* include the centipedes and related arthropods with long, wormlike bodies and many jointed legs. They are all air-breathers and are known from the Devonian to the present.

The *Insecta* include the common insects. This great group constitutes almost three fourths of the entire animal kingdom. They have three pairs of legs and are air-breathers. Insects are known from the Pennsylvanian period up to the present. The earliest insects were the largest ever known, certain dragon flies preserved as fossils having a wing spread of two feet and a body over a foot long (Fig. 221). With a few exceptions, fossil insects are not strikingly different from those which inhabit the earth today.

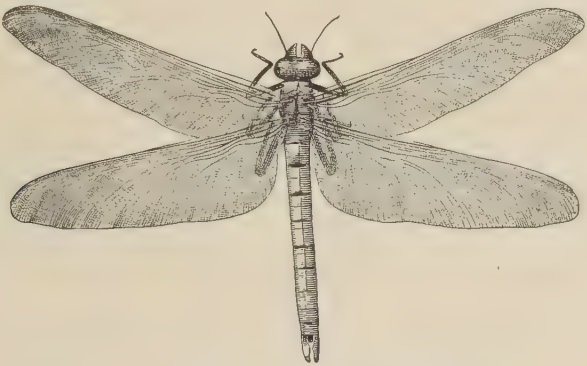

FIG. 221. A giant Pennsylvanian dragon fly. $(\frac{1}{10})$

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9. Vertebrata. All the animals thus far studied have been devoid of backbones and can be grouped as the *invertebrates.* The vertebrates are distinct from all other organisms in possessing (1) an internal jointed rod, or backbone, composed of cartilage or bone; (2) a dorsal nerve cord, whereas the nervous system of invertebrates is ventral — that is, along the under side of the body; (3) highly specialized organs of breathing (gills and lungs), quite different from the respiratory organs of the invertebrates.

Fishes are the lowest type of backboned animals. They live in the water throughout their lives, breathing by gills and moving by means of fins and a flexible tail. The first evidence of the existence of fishlike creatures is a problematical fish scale recently found in the Cambrian rocks of Vermont. In the later Ordovician times primitive fishes were living in the streams of western North America, and broken fragments of their skeletons were laid down in the sea by the rivers and included in the marine sediments. By Devonian times fishes had become so abundant that this period is often referred to as the Age of Fishes. Shark-like forms with skeletons of cartilage became abundant in the late Paleozoic; but the true bony fishes, which are the most abundant variety today, did not become common until the Mesozoic and the Tertiary.

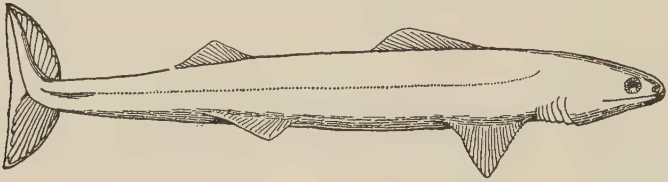

FIG. 222. A Devonian shark

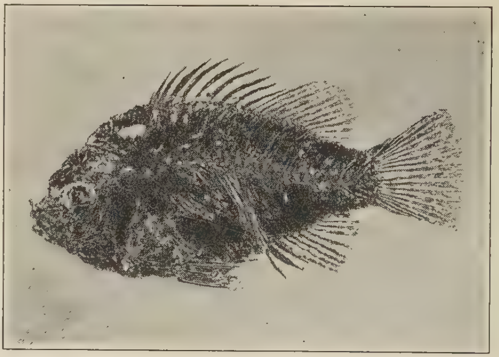

FIG. 223. A tertiary bony fish from Wyoming. (Courtesy of the Field Museum of Natural History)

The *amphibians* are the next-higher group of vertebrates. They include the frogs, toads, newts, salamanders, and similar creatures. Their name, which means "living a double life," refers to the habit of breathing by gills in the early stages of development and by lungs in the adult stage. They mark the transition from the entirely water-living fishes to the land-living higher vertebrates. They are further distinguished from fishes in having limbs instead of fins. The earliest amphibians are the armored *Stegocephalia* ("roof-head"), which are known from the Mississippian to the Triassic (Fig. 224). A single footprint is known from the Devonian. These creatures possessed a head incased in heavy bony plates and, behind the head, a flexible body covered with scales or with a combination of scales and plates. The skin of most later amphibians was naked, or nearly so; and the stegocephalians are in marked contrast with the more modern types, which came in during the Mesozoic and have persisted to the present.

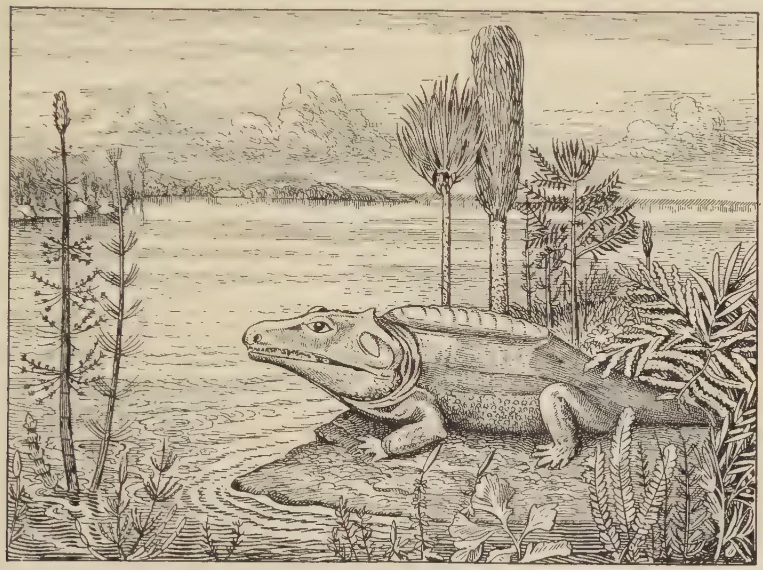

FIG. 224. A stegocephalian in a late-Paleozoic swamp. (Restoration by Williston)

The *reptiles*, like the fishes and amphibians, are cold-blooded animals that have succeeded in moving themselves farther from the water than the amphibians. They lay their eggs on the land, and breathe by means of lungs throughout life. Their skin is usually embellished with scales, or horny or bony plates. Reptiles are first known in the Pennsylvanian, rising to great dominance over land, air, and water during the Mesozoic and continuing, much reduced in numbers, variety, and power, to the present.

The *birds* originated from the reptiles, and are distinguished from them by the possession of feathers and the adaptation of the entire body to flying. Except in primitive forms, birds lack teeth. They are the warmest-blooded animals known. Like reptiles, they lay eggs upon the land. Their eggs are fertilized within the animal's body; in this regard they resemble the reptiles and mammals and differ from the fishes and amphibians, whose eggs are fertilized in the water. Birds are exceedingly rare as fossils. The earliest known bird, *Archæopteryx,* is known from the Jurassic rocks of Bavaria. Although it possessed the teeth, claws, and tail of a reptile, its plumage was that of a primitive bird (Fig. 226). Toward the close of the Mesozoic, birds of a more modern appearance came into existence, and by the Tertiary period there were no longer any birds with teeth.

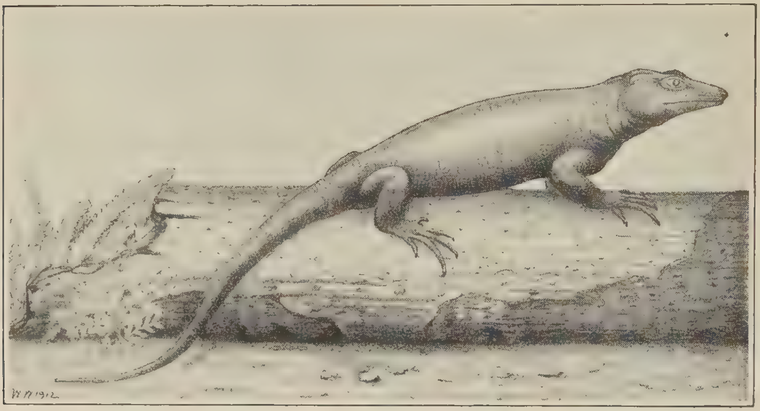

FIG. 225. A primitive fossil reptile. (Restoration by Williston)

The *mammals* are the most highly developed animals on earth. They include the ordinary beasts, such as the lion, tiger, cow, beaver, whale, and the like. Man himself, being a mammal, marks the culmination of evolution in this group. Mammals are warm-blooded vertebrates that bring forth their young alive and that suckle them by means of specialized milk glands. Most mammals are covered with hair. They are first known as fossils in the Triassic. These early types were small and primitive and never succeeded in developing far while the great reptiles held sway. But with the Tertiary the mammals evolved a great variety of interesting forms and became the lords of the lands of the earth. They are still in the full flush of their supremacy. The nervous system of animals, which gradually became more highly developed, reached its finest development in the mammals and especially in the brain of man. With improved brain came increased mentality, by means of which man has had little difficulty in gaining control of the earth. He will maintain this superiority until the coming of a race with higher mentality.

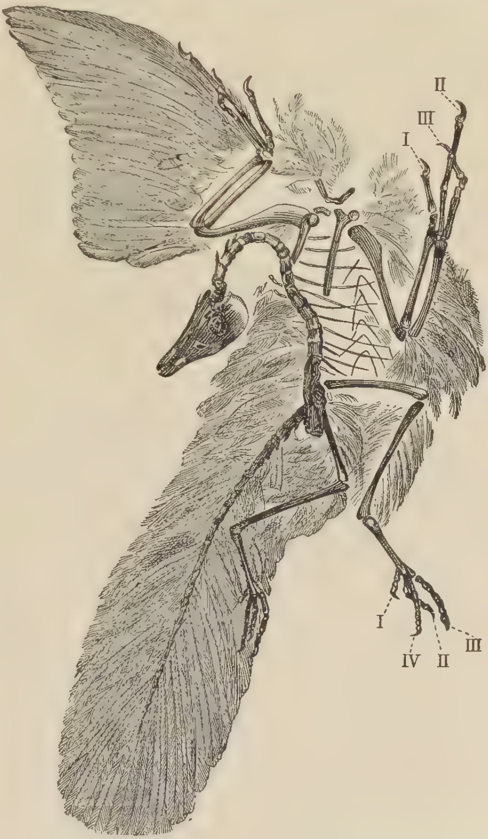

FIG. 226. Archæopteryx, the oldest bird

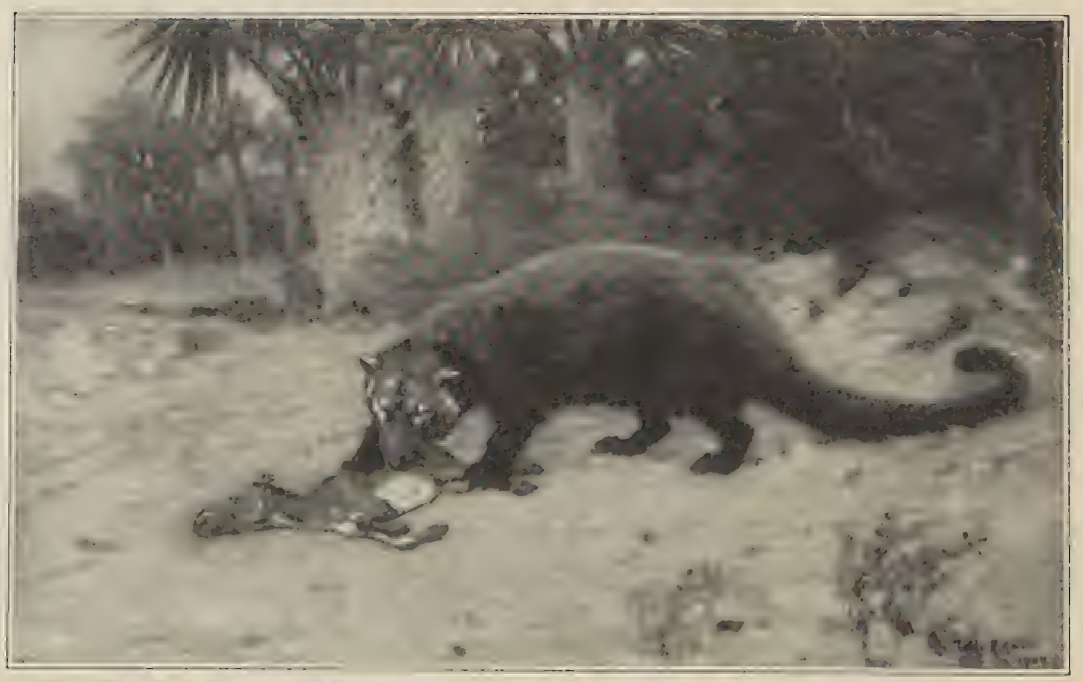

FIG. 227. Early mammal. (Restoration by Charles R. Knight. Reproduced by permission of the American Museum of Natural History)

An Eocene creodont preying upon the carcass of a primitive horse

Chronological Table of the Animal Kingdom [1]

Vertebrates	Mammals	Triassic to present
	Birds	Jurassic to present
	Reptiles	Pennsylvanian to present
	Amphibians	Devonian to present
	Fishes	Cambrian (?) to present
Arthropods	Insects	Pennsylvanian to present
	Centipedes etc.	Devonian to present
	Spiders etc.	Cambrian to present
	Crustaceans	Cambrian to present
Mollusks	Nautilus etc.	Cambrian to present
	Clams etc.	Cambrian to present
	Snails	Cambrian to present
Molluscoids	Brachiopods	Cambrian to present
	Bryozoans	Ordovician to present
Echinoderms	Sea cucumbers	Cambrian to present
	Sea urchins	Ordovician to present
	Starfishes	Cambrian to present
	Blastoids	Ordovician to Permian
	Crinoids	Ordovician to present
	Cystoids	Cambrian to Permian
Worms	Segmented worms	Cambrian to present
Cœlenterates	Corals	Proterozoic to present
	Jellyfish	Cambrian to present
	Graptolites	Cambrian to present
Sponges	Sponges	Proterozoic to present
Protozoans	Radiolarians	Proterozoic to present
	Foraminifera	Ordovician to present

THE PROGRESSIVE DEVELOPMENT OF LIVING CREATURES

The first records of life. Nobody knows exactly where or how the first living things came into existence. According to the doctrine of evolution we should expect to find the simplest forms in the oldest rocks and the more advanced forms making their appearance at successively later periods of time. In general we have found this to be true. In regard to the plant kingdom we have seen that the simple bacteria and seaweeds made their first appearance in the pre-Cambrian, the first land plants in the Devonian, and the higher seed-bearing plants not until the Lower Cretaceous. With the animals, we have seen that certain protozoans, sponges, and coral-like forms are known in the pre-Cambrian, whereas the more advanced types of invertebrates do not appear until the beginning of the Paleozoic. Fishes, the lowest of the backboned animals, are first known from the Ordovician, amphibians from the Devonian, reptiles from the Pennsylvanian, birds and mammals from the Jurassic and Triassic respectively. If all living creatures sprang from some simple prototype, we should expect that prototype to have existed early in the Archeozoic era. It is not likely that such an organism possessed enough body to preserve a record of its existence as a fossil. Even if this had happened, it is probable that subsequent disturbances in the earth's crust would have completely obliterated any trace of such a being. Furthermore, such a prototype would very likely have been entombed in formations much older than the oldest rocks accessible to study.

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[1] All terms have been Anglicized except where confusion might result. Only those forms well known as fossils are included.

Certain microscopic blue-green algæ from Minnesota recently described by Gruner are the only direct evidence of living creatures in the Archeozoic rocks. More striking is the indirect evidence of life in these ancient rocks. Carbon, which is derived from the carbon-dioxide gas in the air through the agency of plants, is very common in the form of graphite in the Archeozoic sedimentary and metasedimentary rocks. Such carbon-bearing formations give fair proof of the existence of life (probably plant life), since carbon — whether in the bodies of living plants and animals or in the form of petroleum, coal, or graphite — is nearly always related to living creatures. The first organisms must have been very simple forms, more like plants than like animals. It is thought by some that the graphite in Archeozoic formations is what remains of the first plants which appeared upon the earth. These plants must have been small, simple aquatic forms. It has been suggested that, through the partial decay of such organisms upon the sea bottom, ammonia was liberated, and this precipitated the lime from the sea water and produced the great thicknesses of limestone (Grenville) known from the Archeozoic of Ontario.

The history of the development of life from the simple water plants of the Archeozoic to the more highly developed plants and animals of the Proterozoic is still an unwritten chapter in the history of the earth. We have seen that the distinction between simple plants and simple animals is often difficult to demonstrate, and there are organisms alive today which may with equally good reason be considered either plant or animal. It is not difficult to imagine the development of simple animals from simple plants, and imagine it we must, since there is no fossil evidence of this stage in life development. It is not unlikely that the earliest organisms combined the characteristics of both plants and animals, and that from these organisms diverged true members of each kingdom.

Fossils are rare in the Proterozoic rocks, but undoubted examples have been collected in various regions. Concretions produced by the life processes of calcareous algæ are in places abundant in the Proterozoic era; and traces of bacteria, the spicules of sponges, worm burrows, and carbonaceous markings attributed to crustaceans have been found. Carbon is abundant in many of the sedimentary rocks of this group, and supports the fossil evidence that life existed during this time.

The rule of trilobites and cephalopods. With the advent of the Paleozoic era living creatures swarmed in the seas, and fossils are abundant in the deposits left behind. All the major divisions of water plants and invertebrate animals are represented by fossils in early Cambrian formations. In the ancient seas of the Cambrian and Ordovician periods trilobites were the rulers par excellence. They were the most active, the strongest, and the most intelligent organisms of their day, and they gained an easy supremacy over the hordes of lesser creatures — the brachiopods, the corals, the worms, and similar forms. Trilobites were the chief meat-eaters and scavengers of the early Paleozoic seas. When threatened they had the power of rolling up like an armadillo and completely covering their soft vital organs with the resistant shell of their backs. In this way they succeeded in protecting themselves against their enemies for long ages of time. The reign of the trilobite must have been one of terror; but although it endured through two of the longest periods of geological time, it was doomed to ultimate failure.

The only creatures in the early Paleozoic seas that seriously threatened the dominance of the trilobites were the nautiloid cephalopods, particularly the straight-shelled variety, which attained to several feet in length. These animals were not only large, but fast-swimming, powerful, and (judging from their single living descendant) aggressive. They did not reach their climax until Silurian time, after the trilobites had begun to relinquish some of their power. The rise of the nautiloids must have been consummated, at least in part, at the expense of the trilobites. It would be interesting to know what might have happened if these two great dynasties of invertebrates had been allowed to wage their war for the supremacy of the sea until one had clearly demonstrated its superiority. Just at the time when it appeared that the cephalopods would overthrow the trilobites, a new race of creatures, the primitive fishes, became abundant, and with ease usurped the power of both contenders.

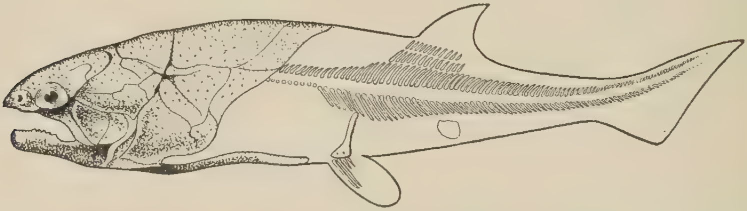

FIG. 228. A Devonian fish with a jointed neck. (After Traquair)

Fishes and the prophecy of vertebrate dominance. The earliest fish remains occur in marine sediments, but the fossils are so badly broken that fishes appear to have first developed in the fresh waters of rivers and lakes and to have been carried to the sea after death. In the Devonian system, where fossil fishes are abundant, there is good evidence that several varieties of these primitive vertebrates had deserted a fresh-water for a marine habitat. Among the early and middle Devonian fishes there were heavily armored forms with jointed necks — a rare feature in this group, since typical fishes have immovable necks. One Devonian fish of this type attained to a length of twenty feet, and without doubt was the most powerful creature living at that time (Fig. 228). Other fishes lacked true jaws and looked like turtles with fish's tails (Fig. 229). Primitive sharks with skeletons entirely of cartilage were present, as well as several varieties of fishes possessing true bones — forms which heralded the evolution of the modern fishes of sport and commerce.

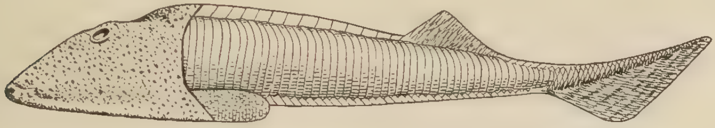

FIG. 229. A jawless Paleozoic fish. (After Woodward)

The origin of the fishes, the earliest of backboned animals, is shrouded in mystery. Their ancestor was probably some wormlike invertebrate without hard parts to leave a fossil record. Their ascendency was slow because they evidently avoided marine water during the early epochs of their racial history. By Devonian time, however, there was no longer any doubt about the ruling power in the sea. The trilobites and cephalopods were forced to yield to the larger, more powerful, more resourceful, and more intelligent fishes. From the Devonian period to the present, backboned animals have maintained their easy supremacy over the invertebrates.

The conquest of the land. Nothing is known of land life, either plant or animal, until the emergence of the scorpions during the Silurian period. These creatures were a few inches long and did not look unlike present-day scorpions (Fig. 230). They developed from the great sea scorpions and, unlike their ancestors, were able to breathe air. They lived along the Silurian strand lines and never strayed far from the oceans, which strongly indicates that other creatures suitable as food for the scorpions had not yet developed organs for breathing air.

The first records of land plants are preserved in Devonian formations. Although primitive, the state of evolution shown by some of these earliest land plants implies an origin earlier in the Paleozoic than the earliest known fossils indicate. It is probable that the first land plants were devoid of woody tissue and hence were unable to leave a fossil record. At any rate, it is known that by Devonian time the lands were clothed in vegetation, as are the lands of today.

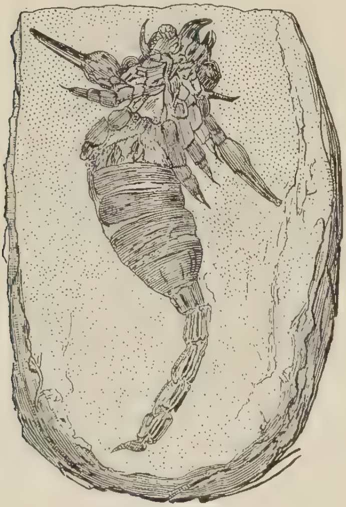

FIG. 230. A Silurian scorpion

With the conquest of the lands by plants came the rise of the higher land animals, the amphibians. Certain Devonian fishes known as the "lung fishes" lived in muddy lakes, streams, and marshes which suffered periodic drought (Fig. 231). The ancient lung fishes, like their present-day descendants, possessed an air bladder that opened into the mouth and supplemented the gills. During periods of drought the lung fishes were able to gulp in air and keep alive by means of this organ. Evolutionists do not believe that land vertebrates were developed directly from the lung fishes, but they agree that they certainly must have originated in some group of fishes possessing an air bladder. The motive ordinarily accepted for the landward evolution of fishes is expressed by Professor Lull, who says that "the more ambitious among the lung breathers, not content with the limitations imposed upon their lives, emerged from the age-long aquatic home and ventured into the new and untried habitat." A more likely explanation would seem to be that the lung-breathing fishes lived out of water only with the greatest difficulty. Their air bladders were at best but makeshift organs of breathing and were never used except when the water became too foul or too scarce to permit the use of gills. The difficulty of breathing through the air bladder is sufficient explanation of the emergence of the fishes: impelled to follow the easiest course, they climbed out upon the land by means of their paired fins, not eager to explore the new environment, but merely to find another body of water where breathing by gills would be possible.

Whatever may have been the incentive for the lung breathers to leave the water, it is true that from them was developed a race of creatures provided with organs for moving about upon land and breathing air. Such creatures are first known in the Devonian, becoming abundant by the end of the Paleozoic era. We have seen that the primitive four-footed land vertebrates were very dependent on the water. The earliest forms (Stegocephalians) were true amphibians, laying their eggs in the water and spending the early stages of their lives in water, breathing through gills. From them came the true reptiles, whose emancipation from the water was more complete, laying their eggs and spending their entire lives on the land. Such freedom paved the way for the great development of reptilian races which took place during the Mesozoic era.

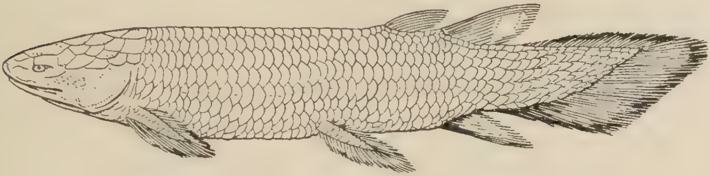

FIG. 231. A Devonian lung fish. (After Dean)

Rise and fall of the great reptiles. During the late Paleozoic the first reptiles were primitive forms. Under the stimulus of the varying conditions of a terrestrial environment they rapidly differentiated, and various races, each adapted to its chosen environment and mode of life, came into existence.

The most interesting of all the reptiles were the *dinosaurs* ("terrible reptiles"). They ranged in size from those as small as a pigeon to gigantic animals a hundred feet long and weighing more than forty tons. Some of the medium-sized dinosaurs were rapacious flesh-eating types, whereas many of the larger species were entirely plant-eating. Some walked heavily on all four feet; others ran lightly on the hind limbs. Some had beaks and feet like birds and undoubtedly had the same ancestors as the birds. Many dinosaurs were armored, some in a most bizarre fashion; others were smooth-skinned. Some lived upon dry upland meadows, some in swampy lowlands; others lived along lakes and rivers, and still others preferred the seashore (Figs. 232–234). With few exceptions their brains were very small, a shortcoming which foredoomed the race to extinction.

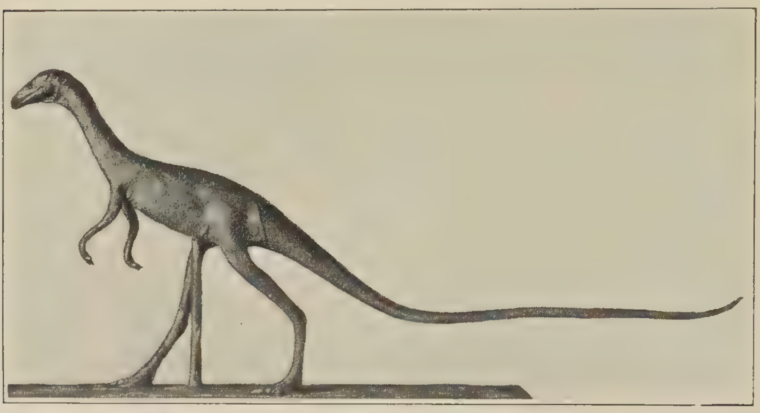

FIG. 232. Restoration of a small, agile, flesh-eating dinosaur from the Triassic rocks of Connecticut. (R. S. Lull, Connecticut State Geological Survey)

Scarcely less striking than the dinosaurs were the *pterosaurs* ("flying reptiles"). The little fingers of the hands of these reptiles were greatly elongated and supported bat-like wings (Fig. 235). They varied from the size of a small song bird to gigantic creatures with a wing spread of twenty-five feet. They were the airplanes of the Mesozoic world. Two races of reptiles (the *ichthyosaurs* and *plesiosaurs*) during this period adapted

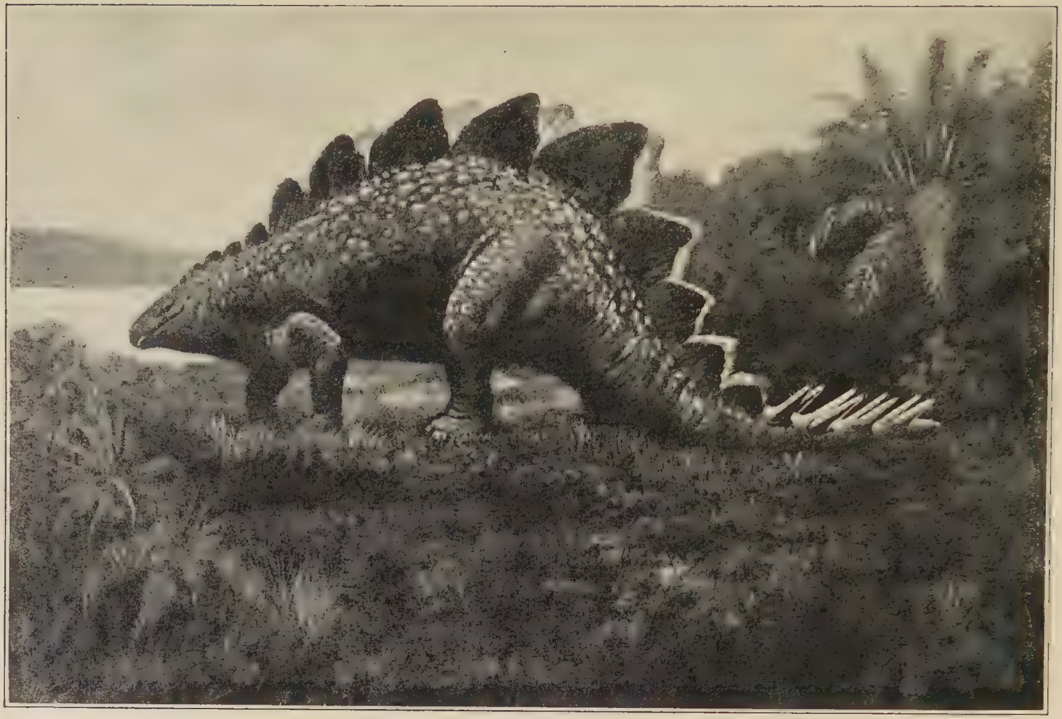

FIG. 233. A heavily armored dinosaur of the Jurassic. (From a painting by Charles R. Knight. Courtesy of the American Museum of Natural History)

themselves to life in the sea, although they breathed through true lungs as other reptiles do (Figs. 236, 237). It is believed that some of the ichthyosaurs did not come to shore to lay their eggs, but brought forth their young alive in mammal fashion. Large turtles, snakes, and lizards also abounded during the Mesozoic. The *mosasaurs* were evolved from a race of land reptiles and took up life in the sea. Some of them were fierce-looking creatures, true sea serpents, attaining to a length of fifty feet (Fig. 238).

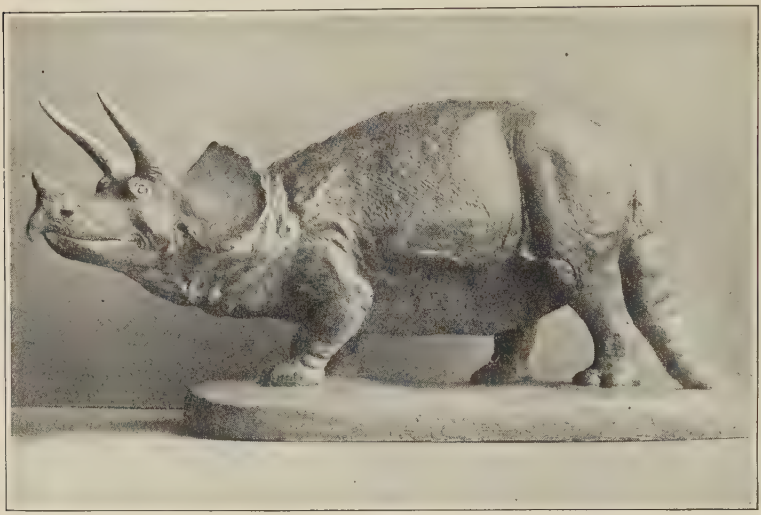

FIG. 234. A gigantic horned dinosaur of the Cretaceous. (Statuette by Charles R. Knight. Courtesy of the American Museum of Natural History)

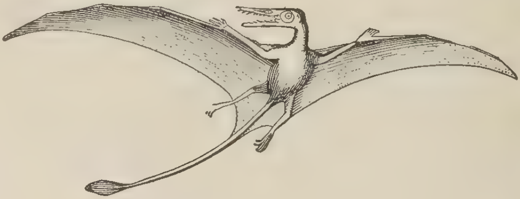

FIG. 235. A flying reptile

The extinction of the dinosaurs, pterosaurs, ichthyosaurs, plesiosaurs, and mosasaurs at the close of the Mesozoic is no less spectacular than the rise of these creatures to dominance over the land, water, and air of the earth. This calamity was due probably to the two vulnerable characteristics of these animals: their low intelligence and their egg-laying habits. The physical changes which terminated the Mesozoic made it impossible for the highly specialized, small-brained reptiles to change rapidly enough to survive the newly imposed conditions. Perhaps even more important was the attack made by the small, primitive, but large-brained mammals on the eggs of the various races of reptiles. With the gradual multiplication of mammals during the Mesozoic, these small animals must have become an increasing menace to the eggs of the larger reptiles, which were laid upon the land but left unprotected. A recent discovery in Mongolia of fossil dinosaur eggs,

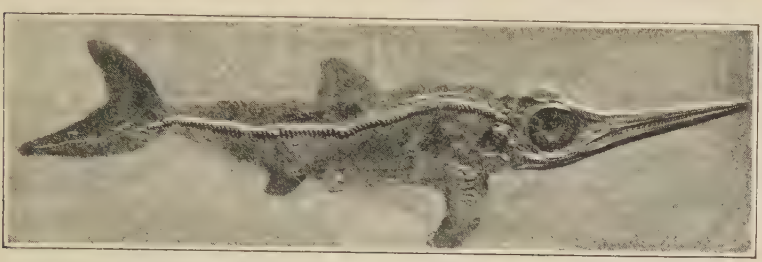

FIG. 236. Photograph of an ichthyosaur, showing the preservation of the flesh as well as the skeleton

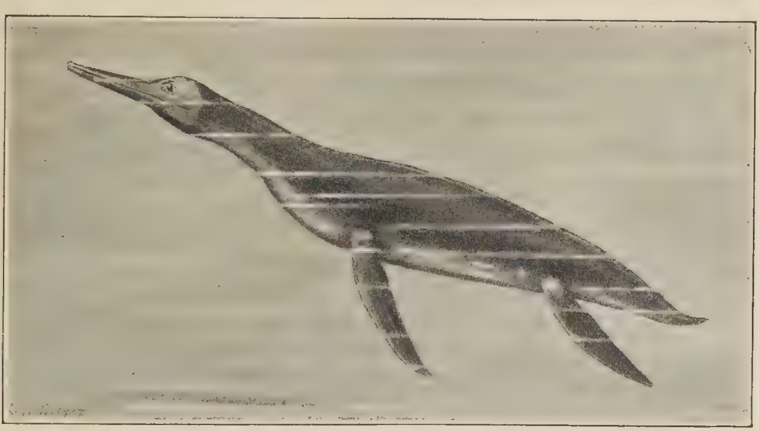

FIG. 237. A plesiosaur. (Restoration by Williston)

intimately associated with the bones of archaic mammals, strongly supports this supposition.

Mammals and the dawn of recent life. Mammals, like birds, were evolved from the reptiles. With their increased mentality the mammals rose rapidly to supremacy after the way was opened for them by the extinction of the powerful but stupid reptiles of the Mesozoic. During this era the mammals were primitive creatures, small and inconspicuous, many of them laying eggs in reptilian fashion. From these types at the beginning of the Cenozoic came the many races of typical mammals that brought forth their young alive. Specialization took various forms. Early to develop were the *creodonts*, mammals with teeth adapted to masticate flesh. From them arose the true *carnivores*, typified by cats, dogs, weasels, and bears; rodents (gophers, rats, etc.), with teeth specialized for gnawing; *edentates* (sloths etc.), in which the teeth are weak; *ungulates* (horses, elephants, goats, etc.),—plant-eating mammals in which hoofs were developed to facilitate escape from the carnivores. Other specialized groups were differentiated early in the Tertiary period (Figs. 239, 240). Like the reptiles of the Mesozoic, the Cenozoic mammals, not

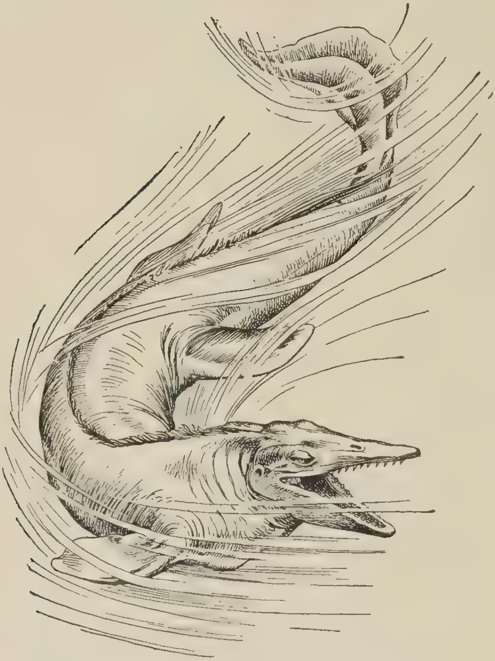

FIG. 238. A mosasaur. (Courtesy of F. A. Lucas and the American Museum of Natural History)

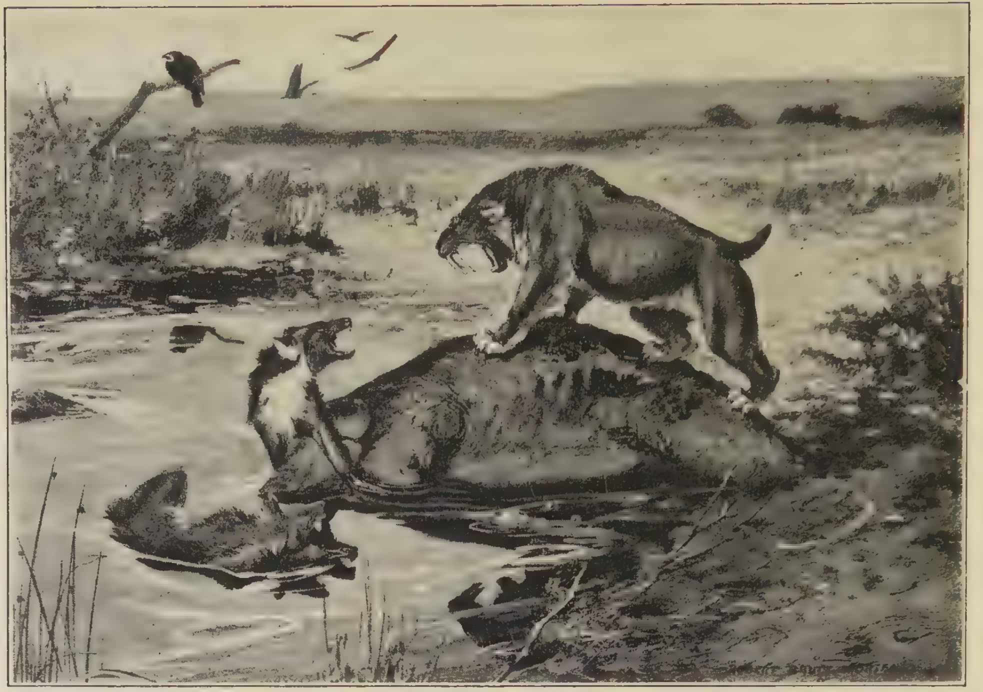

FIG. 239. A Pleistocene tiger and a wolf fighting over the carcass of an elephant. (From a drawing by R. Bruce Horsfall, reproduced, by permission, from "A History of Land Mammals in the Western Hemisphere," by W. B. Scott. Published by The Macmillan Company, 1913)

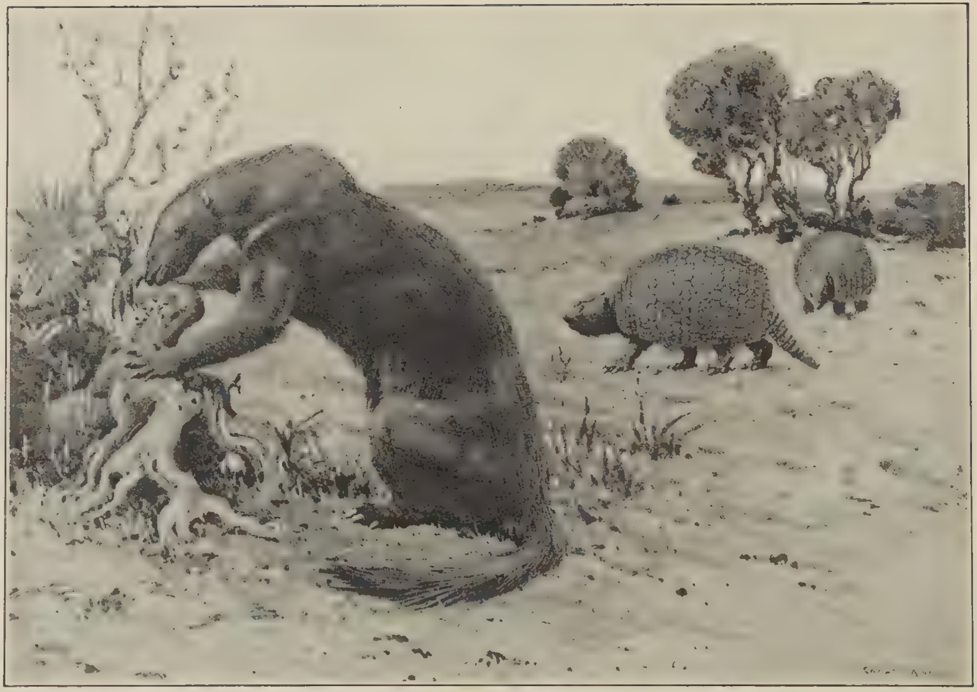

FIG. 240. Restoration of Pleistocene edentate mammals. (From a painting by Charles R. Knight, reproduced, by permission, from "A History of Land Mammals in the Western Hemisphere," by W. B. Scott. Published by The Macmillan Company, 1913)

content with ruling upon land, entered the realms of air (bats) and water (whales, porpoises, etc.). With the passage of Cenozoic time, mammals more and more modern in appearance came into existence. The expansion and development of the various races of mammals is a long story, on which many books have been written. The scope of this book permits of but passing mention. From the human point of view we are chiefly interested in the *primates* (the monkeys, anthropoid apes, and man), mammals having highly developed brains and an erect posture.

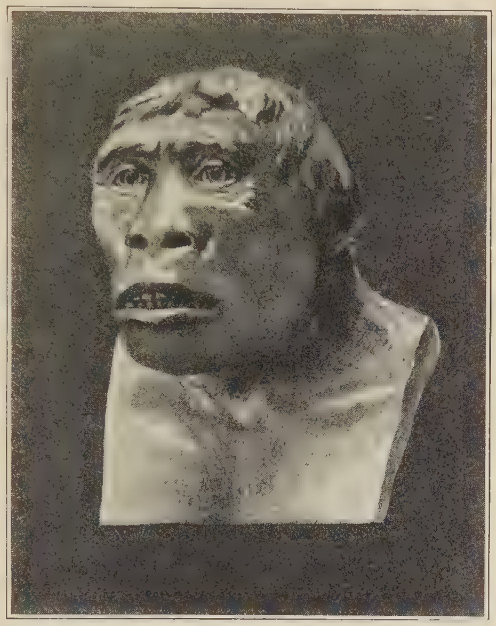

FIG. 241. Pithecanthropus, the Java ape-man. (Restoration by J. H. McGregor. Courtesy of the American Museum of Natural History)

Man, the pinnacle of organic evolution. The fossil records of primates in general and man in particular are scanty, since most primates have been forest dwellers, their remains ordinarily decaying before preservation is possible. Chance has preserved a slight record of early man, however, the few specimens extant having been found, for the most part, in caves and in river gravels.

The earliest known fossil man was discovered in Java in a bed of loose volcanic débris which is uncertainly dated as late Pliocene or early Pleistocene. Only the upper part of the skull, three teeth, and a thigh bone were found. From these remains it is known that the so-called "Java ape-man" (*Pithecanthropus erectus*) combined the traits of man and ape (Fig. 241).

He walked erect, and possessed a brain larger than that of any ape, although smaller than that of modern man. On the other hand, his receding forehead and prominent brow ridges are more apelike than human.

Later Pleistocene deposits have yielded remains of men who are thought to be more nearly in a direct line of evolution to modern man than *Pithecanthropus*. In England the so-called "Sussex man" possessed a brain more nearly the size of that found in living men, but jaws, teeth, and neck more like a chimpanzee's than a man's. The "Heidelberg man," on the other hand, had human teeth but a simian jawbone. The "Neanderthal man" was comparable to the primitive savage of the present day. He lived in caves, made crude stone implements, and could kindle a fire. The "man of Rhodesia" (South Africa) was very similar to the Neanderthals of Europe.

Early man can be classified not only by anatomical peculiarities, but also on the basis of his culture, as shown by tools and implements preserved with the bones. The Pleistocene men have been called "men of the Old Stone Age," because the implements and weapons used by the various races were predominantly of unchipped and chipped stone. The Old Stone Age, or Paleolithic Age, is dominated by stone cultures, and lasted throughout the Pleistocene. With the dawn of Recent time, men of higher culture arose in Asia and spread into Europe. These men of the New Stone Age, or Neolithic Age, not only chipped their stone implements but also smoothed and polished them. There is evidence that they knew the rudiments of agriculture, and the simple arts, such as pottery-making. In time man learned the use of metals — copper first (Bronze Age) and then iron (Iron Age). Old cities of Neolithic man are variously dated from 18,000 B.C. to 12,000 B.C.

With succeeding races of men greater ability to control the elements of the environment developed. In a purely physical sense man has not advanced noticeably since the early Neolithic Age. His progress has been intellectual and social, and he will dominate until a race arises with higher mentality and with better ability to work in coöperative harmony.

CHAPTER VIII

THE GROWTH OF KNOWLEDGE OF THE EARTH

We have turned back the pages of time and have had a glimpse of the vanishing vistas of the past. We have seen how the earth preserves its history in the rocks of its crust, and how a study of processes now active furnishes a key to an understanding of the results of the same processes long ages past. The knowledge of the earth, here only broadly outlined, is the treasured possession of modern science slowly conceived, enlarged, and transmitted through a long line of ardent and thoughtful men. Science, like a tree, is a growing thing, slowly enlarging and changing with time; it is not like a system of philosophy, which may be born today and be succeeded by something entirely different tomorrow. It is a slow journey from the unknown to the known — a journey not without reversals and heart-rending vicissitudes, but always progressive, though the ultimate goal is never within sight and is more of an ideal than an actuality. The slow growth of this knowledge in the minds of men epitomizes in a sense the gradual growth of the earth itself. Many truths that are obvious today were yesterday shrouded in a veil which only the greatest minds could penetrate and only time dispel. Commonplaces of the present grow out of mysteries of the past. Therefore, as we turn our glance backward to the time in man's history where curiosity to know something about the earth on which he lived first arose and was recorded in the writings of the ancients, we must remember that little or no knowledge of an exact nature was available concerning the earth. We must not judge these ancient investigators and their results by the light of present knowledge, but by the darkness of past ignorance. It is true that some of their conclusions seem childish to us and contrary to the obvious. Let us remember that at one time the obvious was the unknown, and that ancient and medieval thinkers had not only to contend with the baffling aspects of natural phenomena but also with the intolerance of the mass point of view, which has always been controlled by emotion rather than by reason and has always curbed and retarded the search for truth. It has always been easier for men to fabricate from a dream false laws to govern conduct and the activity of nature than, by patient and often dull labor, to cultivate recalcitrant truth in a soil of ignorance. We shall see how even men of fidelity to the high aims of science have been befogged by clouds of fancy and consequently retarded in their work. The oppression of mass intolerance is always with us, and the opposition of those who do not know the truth and do not care to know it has notably checked the advance of geology just as it has checked all other sciences. The study of the earth has suffered also from the tendency to speculation, because so much of the globe is beyond the pale of direct observation. In spite of these difficulties geology today rests on a body of well-substantiated facts and holds a place among the important studies of man. Let us see by what avenues it has arrived there.

WHAT THE ANCIENTS THOUGHT ABOUT THE EARTH

Long before geology was placed on a sound scientific basis a great body of speculation concerning the origin, history, and structure of the earth, and a little observation of an exact nature, had been indulged in by several ancient races. Before the Christian Era, Oriental and Greek philosophers had concocted many weird and fanciful cosmogonies, in which their ideas of mythology and religion were intermingled. The oldest of the Greek cosmogonies was that of Hesiod, who conceived of a world originating in primeval chaos and giving birth to the heavens, the mountains, and the oceans, which in turn gave birth to the gods.

Without dwelling on the earlier fabrications of ancient imagination, whose value, if any, was of a literary nature and not a scientific one, let us turn to the countries in the Mediterranean basin, where during the time of Aristotle (384–322 B.C.) an intelligent appreciation of geological phenomena was beginning to take form. Aristotle and his followers represent the high-water mark of scientific achievement among the ancients, both in speculation and in empirical observation.

Surface processes. Aristotle gave not a little attention to the surface agencies which denude the earth. He studied and correctly understood much about the rivers entering the Mediterranean on the north. His writings are voluminous. Thus we find him ridiculing the belief of his master, Plato, that rivers originate in a great subterranean reservoir within the earth. He points out the fact that the large rivers flowing into the Mediterranean rise in high, mountainous country, and presents the view that mountains condense the moisture in the atmosphere, absorb it, and subsequently discharge it into channels which grow into rivers. He likewise observed from studying the Nile that rivers deposit material on flood plains and build up the lands. Herodotus, however, a century before, had formed the idea that Lower Egypt had once been covered by the sea, had recognized the significance of the yearly deposit of silt laid down by the Nile upon its wide flood plain, and had concluded that "Egypt is the gift of the river."

Second only to Aristotle among early Greek observers of natural phenomena was Strabo (born about 63 B.C.), a great traveler and historian, author of a geography of seventeen volumes. Strabo described the formation of deltas and alluvial plains by rivers and made observations concerning the origin of mountain ranges and vulcanism which we shall presently see entitles him to a position nearer to modern observers than to ancient.

In Rome the greatest scientist of his day was Seneca (about 4 B.C. to A.D. 65). He made observations on the constructive and destructive processes of water, and formulated accurate conceptions of the transportation of sediments by rivers and the chemical action of underground water. He conceived of the earth as originating in a watery chaos, and believed that some day a deluge of world-wide extent would come which would annihilate the races of men.

Subterranean processes. Because of the location of Greece and Rome in a belt of frequent seismic shock and volcanic ebullitions, thought turned early to the contemplation of underground forces. Thus Anaxagoras, in 480 B.C., explained earthquakes by the rushing of the ether into subterranean caverns; Democritus (460?–357? B.C.), by the rupturing of the earth after heavy rains and the liberation of liquid material; Anaximenes of Miletus (544 B.C.), by the drying of the water-bloated earth and the consequent disruption of the mountains. Aristotle, commenting on these views, shows that, according to them, earthquakes should grow less frequent and severe, which is not the case. He stated that the earth is naturally dry inside, but that after heavy rains it becomes moist. By an intermingling of "moist" and "dry" within the earth, winds are generated which rush madly about and cause the disturbances displayed at the surface as earthquakes and volcanic activity. The idea that vulcanism was caused by imprisoned winds in subterranean cavities was very generally believed by the ancients. Thus Æolus, the god of the winds, was supposed to live under the Æolian Isles, where eruptions have been frequent and severe. The idea that earthquakes are associated with peculiar weather conditions is a myth which persists even to the present among credulous people, who may be heard to pass sober remarks about "earthquake weather."

Lucretius, in "De Rerum Natura," paints a poetic picture of the earth's interior according to the prevalent Aristotelian view, with great wind-swept cavities, lakes, rivers, cliffs, and gorges resembling those on the surface. Explaining the eruptions of Mt. Etna, he states that such mountains are hollow, and that the raging winds within them heat the rocks until they burst into flame and cause a vent to be opened in the top of the mountain for the expulsion of molten rock, ash, and smoke.

As late as the beginning of the Christian Era we find Strabo attributing vulcanism to the force of winds in the interior of the earth. In Strabo's time Vesuvius was dormant and was not known ever to have been active. The great geographer, however, detected the volcanic nature of the cone and recorded its previous history with some exactness.

Seneca at this time studied the literature of earthquakes and wrote on the types of motion which earthquakes produce in parts of the earth's crust. He explained earthquakes by the double action of expanding gases and the collapse of underground cavities. He attributed the heat of volcanoes to the friction produced by rushing winds.

Pliny the Elder (A.D. 23–79), in his "Naturalis Historia" (a work of thirty-seven volumes which touched on nearly every branch of science), wrote on volcanoes but added little to the views then current. It should be remembered, however, that he was an untiring student of natural history, and lost his life in studying the great eruption of Vesuvius in the year 79 of the Christian Era.

None of the ancient Greeks or Romans went far in explaining the nature and causes of underground processes. Winds blowing in subterranean cavities, igniting sulphur, coal, and other inflammable substances in the rocks, were almost universally invoked as the cause of vulcanism.

Earth history. The remains of well-preserved fossils are common in the Mediterranean basin and were early remarked by the inhabitants. It is recorded that Xenophanes, who lived during the sixth century before Christ, discovered fossils on Malta, recognized their true nature, and made the deduction that the land suffered periodic submergences from the sea. About two hundred years later Xanthus came to a similar conclusion concerning marine fossils found in Armenia. Herodotus and Eratosthenes (276?–196? B.C.), because of the fossils and the salt formations found in Egypt, were likewise convinced that the sea had invaded that land.

We have seen that Aristotle gave much thought to the work done by surface agencies of erosion in modifying the land. He expressed the changes which the face of the earth undergoes better than did any of his predecessors and contemporaries.

He fully realized how slowly these changes took place — so slowly, in fact, that "whole nations may disappear without any recollection being preserved of the great terrestrial changes which they have witnessed from beginning to end." Aristotle likened the changing earth to the seasons, and attributed large importance to the greater power of high areas to absorb moisture from the atmosphere than the low lands. Thus, he declares in regard to the history of Egypt:

> It is clear that, as time never stops, and the universe is eternal, the Tanais and the Nile, like all other rivers, have not always flowed; the ground which they now water was once dry. But if rivers are born and perish, and if the same parts of the land are not always covered with water, the sea must undergo similar changes, abandoning some places and returning to others, so that the same regions do not remain always sea or always land, but all change their condition in the course of time.

Such a statement is strikingly modern in its philosophy and might have been made by a geologist of the twentieth century.

Aristotle saw in the past history of the earth an analogy to the life history of a plant or animal, with periods of growth, maturity, senescence, and decay. He held the fanciful belief that at various times of rejuvenation in the earth lower animals originated in mud by spontaneous generation and gave rise by sexual means to the higher types of animals. He realized the close relationship of plants and animals and thought that the former were linked to the latter by a long series of transitional forms.

Strabo concurred with his predecessors in the belief that fossils found in the rocks were the remains of creatures that once lived in the sea. He not only inferred the former presence of the ocean over regions which are now dry land, but he went further, believing that the same area may alternately rise and sink with reference to sea level and that such movement may be local or of continental magnitude. He not only realized the changes wrought in the earth's crust as demonstrated by fossil remains, but advanced a remarkable theory to explain such changes. He observed that new land was erected in the ocean as a result of volcanic activity, and believed that volcanoes acted as safety valves for the escape of subterranean vapors. When the underground furies can no longer be contained, vulcanism results, with its attendant effect on the lands, submerging some and elevating others.

In the foregoing paragraphs we have sketched only a few of the observations and speculations made by the ancients about the earth. What of value to modern science is to be had from the work of these early people? The answer in regard to the Eastern races, whose fanciful conceptions we have not taken space to relate, is that almost nothing of scientific value either philosophical or empirical was produced. The philosophical speculations of the Greeks and Romans, it is true, sometimes partly agree with conceptions of the present day; but it must be remembered that where early hypotheses came close to the truth they did so, practically without exception, through chance and not because they were based on carefully observed facts. While some sound observations were made, as we have seen, the easier way of *speculation* as to the causes of things was almost the universal rule.

One great forward tendency can be observed in the writing of the ancients, and that is the gradual abandonment of the classic tenets of paganism. The primitive belief that nature was controlled by the wills of divinities possessing human virtues and vices gave way slowly to the recognition of natural laws, immutable and unchangeable. The growth of the new idea was happily not dwarfed by opposition of church or public opinion, so that all manner of views were freely expressed. This golden age of tolerance lasted well beyond the rise of Christianity, but unfortunately came to an end in the Middle Ages.

In such an environment science should have reached a great height of development. It failed to do so because the temperament of the people was not suited to the laborious methods by which — and by which alone — a firm structure of truth is to be erected. Von Zittel, in summing up the shortcomings of the ancient philosophers as geologists, says:[1]

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[1] Karl Alfred von Zittel, History of Geology and Paleontology. 1901.

Not a single writer of the ancient world showed any interest in the firm earth crust, not one observer gave a thought to the composition of rocks. Not the most acute thinker of those cultivated peoples had even a shadowy premonition of the value that might appertain to fossils as witnesses of a sequence of events in the history of our earth. None suggested that our planet might have passed through a succession of changes before attaining to its present physical condition and configuration; still less, that particular phases in the history of change might be deciphered from the character and superposition of the rocks. The evolution of the earth and its denizens, which is at the present day the great problem of geological and biological research, played no part in the literature of antiquity; fanciful hypotheses and disconnected observations cannot be acknowledged as scientific beginnings of research.

THE SLOW GROWTH OF AN INFANT SCIENCE

After the fall of the Roman Empire, war, revolution, and intolerance nearly exterminated learning in Europe. Such culture as survived took refuge in monasteries and in cloistered academies. Unfortunately for the natural sciences, this culture concerned itself little with the realm of nature, merely accepting without serious doubt the teachings of Aristotle. From A.D. 800 to 1300 the spirit of the ancient world was kept alive by the Arabs alone, who purchased and translated into Arabic many of the Greek and Roman scientific treatises and saved for posterity much of the old learning which otherwise would have been lost. In addition, they enlarged by their own investigations the sciences of mathematics, astronomy, medicine, and biology, but paid little attention to the studies of the earth which are grouped under geology. Hence it was not until the fifteenth century, with the rebirth of learning in Europe, that the earth sciences once more came into their own, after languishing for nearly fifteen hundred years.

We have seen that the ancient Greeks and Romans had realized that fossils were the remains of plants and animals. It was generally believed that the presence of fossils high among the rocks of the continents proved that the sea had submerged the land, bringing with it a teeming horde of denizens which were abandoned by the waters when they withdrew. During the black days of bloodthirsty orthodoxy which came with the ascendency of the Church, such a view had to be suppressed or disguised if the unfortunate scholar was not to be persecuted or assassinated. It was written that land and sea were separated on the third day of creation, and that on the fifth animal life began. In spite of overwhelming evidence to the contrary, it could not be true that the sea cast animals on the land before animals existed or after the sea and the land had been separated. Furthermore, to those who studied the occurrence of fossils it was apparent that long ages of time had been involved, — another heretical belief, since it was thought that Scripture had placed the creation some brief six thousand years before. Thus we find the attempt to harmonize nature and the narrow dogmas of the time. It was denied that fossils were once alive. An old idea that fossils were an abortive attempt of nature to create plants and animals received new life at this time. Thus fossils were called *lusus naturae* and were thought of as "freaks of nature."

With the beginning of the fifteenth century a long and ridiculous controversy concerning the nature of fossils arose, — a controversy which lasted three centuries and which is still an open question in the minds of a few ignorant people today. Were fossils the result of a creative force in nature, unsuccessfully striving to produce living things? Were they living seeds transported from the sea in vapors or from some hidden womb within the earth? Were they merely deceptive concretions of mineral matter contrived by the devil to mislead the minds of men? Some of the more subtle of the disputants, unable to belie the evidence for the organic nature of fossils, but forced to bring this view in accord with the dogmas of the Church, hit upon an ingenious subterfuge, the Deluge of Noah. The Flood was just the catastrophe necessary to explain the occurrence of fossils to those who knew nothing about the problem. So it was that the diluvialists arose, men who believed that the Deluge of one hundred and fifty days was sufficient to have caused the orderly disposition of fossils in layers amounting to many thousands of feet in thickness. The reasoning of the diluvialists proceeded from the combination of a very scant knowledge of fossils and their occurrence with a strong desire to keep their views within the narrow bounds of the medieval theology. As champions of orthodoxy this group became a powerful unit in the long controversy over the nature of fossils.

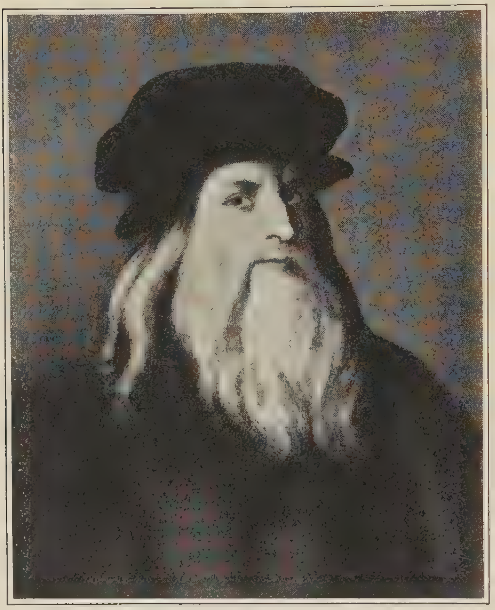

FIG. 242. Leonardo da Vinci

Some of the greatest men of their day ventured opinions as to the origin of fossils. Most illustrious of all, perhaps, was that man of universal genius Leonardo da Vinci (1452–1519), a painter, architect, sculptor, musician, engineer, mechanician, athlete, natural philosopher, and man of the world. He had seen the abundantly fossiliferous rocks of northern Italy while he was engaged in excavating canals in that region during his youth. He clearly saw that the sea had brought in sediments and with them the remains of snail shells and other denizens of the deep. His explanation was clear and correct, and ridiculed the belief that fossils could have originated in the rocks under the influence of the stars, a hypothesis then popular. The learned Fracastoro (1483–1553), physician and professor of philosophy at Padua, expressed clearly his views about fossils, which accorded with those of his compatriot Da Vinci. He denied the formation of fossils as the result of a plastic force struggling toward creation, and maintained that fossils could never have been left by the Flood, which was of short duration and would have scattered shells over the surface of the land instead of burying them deeply in the earth.

The fifteenth and sixteenth centuries in Italy were not a time of rich harvest for the sciences, although an awakening interest in reality was dawning in most of the civilized world. While the bulk of interest manifested in nature took the shape of futile controversy, men like Leonardo and Fracastoro shone with unusual brilliance. Other Italian writers of this period, taking their cue perhaps from their more illustrious contemporaries, expressed remarkably sound views concerning the origin of fossil shells.

In Germany during the sixteenth century the most distinguished student of the earth was Georg Bauer, more widely known under the pen name of "Agricola" (1490–1555). Bauer was a pioneer in the study of minerals and mining. His magnum opus, "De Re Metallica," gives a description of mining and metallurgy as practiced in his time, and information concerning the occurrence of valuable minerals. Agricola has been called the Father of Metallurgy. His interests were not confined to minerals and mining, for he wrote extensively on the nature of fossils. His acumen in this regard was sadly inferior and led to a classification of almost all the organic remains studied with the inorganic substances, which were his chief concern. The hardest obstacles to remove from the path of an expanding science are the erroneous ideas of its leaders; hence, although the science of mineralogy was greatly advanced by the fine work of Agricola, the study of paleontology was retarded by his rather superficial judgments on the nature of fossil remains.

At about the same time in Switzerland, Konrad von Gesner (1516–1565) published in the year of his death the first illustrated work on fossils. In this the author discusses fossils, as well as minerals, concretions, and other inorganic bodies, with little discrimination, after the habit of his day confusing specimens of a clearly organic origin with those of inorganic nature. Many other names of sixteenth-century writers who treated the fascinating subject of fossils could be mentioned. In all the important European countries there were men who became interested in this phase of geology, and fossils became more widely known; but not until the middle of the eighteenth century was there any unanimity in the belief that fossils represent creatures which were once alive in the seas and on the lands of the earth.

The seventeenth century gave to geology a man who did more than any other to lead the way to sane beliefs regarding many controversial subjects. Nicolaus Steno (1638–1686?), a Dane, who studied medicine and gradually worked his way to a professorship of anatomy at Padua, published in 1669 an explanation of the origin of marine and fresh-water deposits, and an interpretation of their fossil contents. His remarks about sedimentary formations have a strikingly modern tone; in fact, a large part of the so-called modern stratigraphy was anticipated by this seventeenth-century savant. Sir Archibald Geikie summarizes the ideas of Steno as follows:[1]

> The strata of the earth are such as would be laid down in the form of sediment from turbid water. The objects enclosed in them, which in every respect resemble plants and animals, were produced exactly in the same way as living plants and animals are produced now. Where any bed encloses either fragments of another, and therefore older, bed, or the remains of plants or animals, it cannot be as old as the time of the creation. If any marine production is found in any of these strata, it proves that at one time the sea has been present there; while if the enclosed remains are those of terrestrial plants or animals, we may suspect the sediment to have been laid down on land by some river or torrent.
>
> Steno established by direct observation some important axioms of stratigraphy. Every stratum, he said, has been laid down upon a solid subjacent surface. The lowermost strata must have become firm before the uppermost were deposited. A stratum must originally have terminated laterally against a solid body or else must have extended over the whole earth, so that when the truncated ends or edges of strata are exposed, we must either seek for evidence of their former prolongation or for the solid surface against which they

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[1] Archibald Geikie, The Founders of Geology (1905), pp. 55–56. Reprinted by permission of The Macmillan Company.

ended and which kept their materials from slipping down. As each bed at the time of its formation was covered only with fluid, when the lowest member of a series was laid down none of those above it had yet been deposited.

Steno recognized that the original position of sedimentary formations was horizontal, or nearly so, and that when they are inclined, as is true in so many cases, they have been subjected to disturbance. Throughout his writings there is evidence to show that he realized that the strata of the earth's crust preserve the records of a sequence of events. He thoroughly understood the great influence of running water in carving the hills and valleys of the land, and the control of the effects of erosion by the character of rock formations. All in all, Steno was an anomaly in the seventeenth century and at least a hundred years in advance of his time.

As on the Continent during this period, so it was in the British Isles: the infant science of geology was struggling for expression. The first practical suggestion for a map which would show the different surface formations of the earth's crust as well as the important mineral and fossil localities was made to the Royal Society in 1683 by Martin Lister. Lister was a keen student of living shells and compared recent and fossil forms in a masterly way, but concluded ridiculously that the fossil forms had never been alive and were but crude copies of real animals — frauds of nature produced in the rocks in a manner which (let it be said to his credit) he did not attempt to explain.

Robert Plot, an antiquarian at Oxford, figured many fossil shells in a work on the natural history of Oxfordshire published in 1677. He concluded that fossils were due to a "plastic virtue latent in the earth." His successor, Edward Lhuyd, in 1699 figured and described many more fossils from the same region and came to the modest conclusion that fossils result from moist seed-bearing vapors which are generated in the ocean and later insinuate themselves into the rock strata, where they give birth to their marvelous offspring. Such ideas were no advance over the speculations of the ancients and furnish good examples of the fruitless and unscientific beliefs of the time.

Perhaps the worst fiasco accomplished by any of the misguided students of natural phenomena during this period was the sad experience of Johannes Beringer, professor in the University of Würzburg. In 1728 Beringer published a work on fossils in which a number of bona-fide fossils were illustrated, as well as such unusual forms as Hebrew letters and even stars and the sun and moon. The climax was reached when the unfortunate professor found his own name in the rocks, apparently preserved as a fossil. This was too much for even this gullible man to accept, and he learned to his dismay that he had been duped by a group of irreverent students who made the remarkable "fossils," planted them in the rocks, and then led the trusting professor to the locality where he proceeded to make the great discoveries. Some of these spurious fossils are still to be seen in several German museums.

Theories of the origin and structure of the earth were no less fanciful than those concerning the origin and nature of fossils. In 1681 Thomas Burnet, an English divine, published the "Sacred Theory of the Earth." Among other absolutely original ideas embodied in this work was the assertion that before the Deluge the earth was a true paradise, but that because of man's wickedness the sun's rays caused the earth to crack open, allowing the waters imprisoned within to overflow all the inhabited world. As an attempt to support the orthodox religion of the time this book was enthusiastically received, although it contained not an iota of scientific truth. In similar manner William Whiston published, in 1696, the "New Theory of the Earth," and in the previous year John Woodward published his "Essay toward a Natural History of the Earth." Both these English works attributed large importance to the Deluge and were fanciful in the extreme. Woodward, however, deserves credit for realizing that fossils must be the actual remains of plants and animals and not mere sports of nature.

The writings of these English cosmogonists were destructively criticized in 1740 by the learned Italian abbot Antonio Lazzaro Moro. Moro derided the conception that the Deluge could account for the occurrence of fossils, and attempted to explain the phenomenon by observations on the present activities of natural processes. Although Moro discarded the Flood as an important event in the earth's history, he was careful to keep within the restrictions of Genesis. His cosmogony overstressed the importance of vulcanism; it was more thoughtful than those of Burnet and Woodward, but it added little to the progress of science.

Not to be thought of in the same way as these fruitless dreamers was the gifted Robert Hooke, one of the finest minds of the seventeenth century. As Curator of Experiments to the Royal Society, he presented to that society, in the year 1688, his "Discourses of Earthquakes." Although he demonstrated many facts concerning the manifestations of diastrophism and vulcanism, he contributed nothing to the explanation of the cause of either, believing both to be the results of "the general congregation of sulphurous, subterranean vapors." He recognized the truly organic nature of fossils, but believed it impossible to erect a chronology of events in the history of the earth from a study of such ancient remains.

John Ray, the ablest biologist of his day in England, took a lively interest in the papers of Hooke and Woodward, and was led to make investigations of his own in the field of geology. Some of his suggestions were ingenious and stimulating, but represent no real advance in the science of geology. Ray stood firm to the last in his opinion that fossils were never parts of real, living plants and animals. John Ray and Martin Lister perhaps knew more about fossils than any of their contemporaries, and to find them both denying the organic nature of such remains is a sad commentary on the ecclesiastical prejudices of the time.

From the middle of the seventeenth century until well into the eighteenth there appeared from time to time several rationalistic philosophers whose names are better known in connection with their systems of philosophy than for their contributions to geology. Such a man was the illustrious Descartes (1596–1650), who invented a cosmogony published in his famous work "Principia Philosophiae." Here is a complete history of the earth, a figment shaped by the imagination of one of the world's best thinkers. As such, it leads to its conclusions in a clear and logical manner; and if the original premises were correct, it would surely be true. Unfortunately, Descartes was so enamored of the contents of his mind that he failed to check up his conclusions with the facts of nature; consequently his cosmogony must go by the board and join those of his less-gifted contemporaries.

Second not even to Descartes as a philosopher was the great physicist and mathematician Leibnitz (1646–1716). The problem of the origin of the earth was only one of the many topics that interested him. In a book in every way remarkable, the "Protogaea," published in 1749 (long after his death), his cosmogony was stated more fully than ever it was during his lifetime. While we cannot give the details of his scientific views here, it should be said that some of his beliefs are accepted by physicists today. He apprehended the effect of the earth's internal heat on the phenomena of igneous rocks, as well as the rôle of surface waters in altering the outer part of the earth's crust. He pointed out the absurdity of grouping minerals and fossils together as the results of the same plastic force in nature, and scouted the idea that because nature offered no living counterparts of fossil creatures, fossils were never parts of living things. He hinted at the evolutionary process which explains this situation when he asked, "Is it not to be presumed that in the great changes which the earth has undergone, a great many animal forms have been transformed?" The cosmological and geological theories of Leibnitz suffer, as do those of his contemporaries, from the attempt to make the history of the earth harmonize with the Mosaic story of creation.

The work of the French traveler and diplomatist Benoît de Maillet (1656–1738) must at least be mentioned in an account of the growth of geology, since his book the "Telliamed" (the author's name spelled backward) had some influence on the progress of earth studies, although he was not strictly a man of science. De Maillet considered all the rocks of the earth as formed by the oceans, in striking contrast with Moro, who believed that all the surface features of the globe had been produced by volcanic activity. Perhaps the most original of all the cosmogonies of this period, De Maillet's story consists of many carefully observed facts braided with beliefs which are at the same time whimsically charming and ridiculous. Thus he tells of mermen and mermaids, of their evolution into land-dwelling men of outlandish appearance, giants, dwarfs, and apelike creatures. He believed that the transition from mermen to ordinary men is best made in the polar regions, although, as he soberly states, since not all the species of mermen are known, it is not possible as yet to trace the descent of the various races of mankind.

The last of the great line of eminent cosmogonists was the illustrious Frenchman Buffon (1707–1788). He voiced the feeling, grown strong by the middle of the eighteenth century, that the previous students of the earth had allowed speculation to take the place of careful observation of nature, and that the literature of earth science was cluttered with weird and fantastic doctrines for which there was no support. He published a theory of the earth in 1788 which in scope, sanity, and beauty of expression surpassed all previous cosmogonies. He recognized many of the facts which are now thought of as the "principles" of geology: the great antiquity of the earth and the gradual but tremendous changes which its surface has undergone. He understood the destruction wrought by sea and river, and the succession of animal life upon the earth. Ecclesiastical opposition, still a powerful obstacle to the progress of science, caused Buffon's masterpiece, "Époques de la nature," to be censured at the Sorbonne, because in it the author stressed the great duration of the successive epochs in the earth's history. The weakness of Buffon's work consisted in either disregard or ignorance of the important results of Steno's work and the findings of other men who, we shall see, had placed geology upon a firm scientific basis.

The early part of the eighteenth century saw a growing knowledge of fossil remains and a slow abandonment of the belief that fossils were but sports of nature. It became the craze to collect the so-called "figured stones." Arduino and Vallisneri were ardent collectors in Italy, G. W. Knorr and J. E. I. Walch in Germany, and J. J. Scheuchzer in Switzerland. Arduino (1713–1795), professor of mineralogy at Venice, was one of the most brilliant stratigraphers of all time, and enlarged the knowledge of Tertiary fossils and formations by his studies. Vallisneri (1661–1730) collected marine fossils on both sides of the Apennines and protested against the Deluge explanation of their positions in the rocks. He accepted the idea that relative changes of the level of the earth's surface may have caused the sea to inundate places which were formerly dry land, and that the ocean creatures as they died fell to the bottom and were buried in the deposits. Later the sea withdrew, leaving its deposits high and dry on the newly formed land surface. Knorr (1705–1761) and Walch (1725–1778) collected and described many types of fossils, both plants and animals, and summarized the work of previous paleontologists. Without doubt the work of these last two men greatly surpassed any of the previous studies of fossils. Scheuchzer (1672–1733), of Zürich, published extensive descriptions of fossils, which he first called "figured stones" and considered inorganic freaks of nature; but later he decided that they were relics of the Deluge. Throughout his life he was hoping to find fossil remains of human beings. Toward the end of his life he found a skeleton which seemed to fulfill this hope, the remains of what he believed to be "one of those infamous men whose sins brought upon the world the dire misfortune of the Deluge." He described this specimen in 1726 as "the man who witnessed the Flood" (*homo diluvii testis*). Later this famous "man" was shown to be a giant salamander, although it is nearly as large as a man.

While Germany, Italy, England, and Switzerland were thus slowly groping through a maze of speculative and controversial ideas in search for knowledge and the truth about the origin of fossils, France was advancing far more slowly. It is true that as early as 1580 Bernard Palissy published his observations on fossil woods and animals, citing them as evidence for the former presence of water over areas which are now land. Not forgetting Buffon, who was a brilliant theorist but a poor observer, France did not produce a man who could stand among the founders of geology as a real science until the coming of Jean Étienne Guettard (1715–1786). Guettard was the first master of geographical geology, and spent large effort in depicting scientific knowledge by means of maps. He compiled maps of France and England which showed the local occurrence of rocks and minerals, as well as fossil localities, coal seams, quarries, mines, and springs. For accuracy in detail these maps compare favorably with the geological maps of the present day as far as they go, but they give no clear idea of the sequence of formations or of the structure of the rocks. Nevertheless, as a pioneer in geological cartography Guettard deserves a place high among the early students of earth science. In addition to his work on maps, he produced about two hundred papers covering a wide range of scientific subjects. He described accurately the destructive processes of denudation, recognized and described the fossils which he found in the rocks, and, certainly not least of all, was the first to recognize the extinct volcanoes in central France, now far removed from any active volcano.

Nicolas Desmarest (1725–1815), another Frenchman, continued the work of Guettard in the old volcanic region of Auvergne. Guettard, in conformity to the prevailing belief of the time, drew a distinction between lava and the dark, prismatic volcanic rock still known by Pliny's name *basalt*. Basalt was well known to mineralogists as the rock in the famous Giant's Causeway in Ireland, but the nature and the origin of this rock was a matter of hot debate. To Desmarest is due the credit of proving that the basalts of the Auvergne region had actually been extruded from the craters of the extinct volcanoes at a time when these were active; and although erosion had obliterated all these ancient craters, he demonstrated the points of common origin for several basalt flows.

THE FOUNDING OF GEOLOGY AS TRUE SCIENCE

After the middle of the eighteenth century the reaction against footless speculation, which had started with the sane observations of Guettard and of Desmarest, became more pronounced, so that with the inauguration of the nineteenth century the science of geology was placed upon a strong foundation of fact. The span of years from 1790 to 1820 was one of the most fruitful in the history of geology; it has been called the Heroic Age of Geology. This period saw the rise of geological travel, with expeditions into the desolate upland plains of Siberia and the unknown wilderness of the mountains of Asia and America. One of the most noteworthy expeditions of this type was intrusted to the highly gifted Pierre Simon Pallas (1741–1811) by the Russian government. For six years, suffering unbelievable hardship, Pallas explored the plains, rivers, and lakes of eastern Russia and Siberia as well as the Altai and Ural mountains. In a three-volume work he described the wealth of material he had gathered and the new things he had seen during his travels. His book is rich in information concerning the plants, animals, geography, and geology of the region. Most important of all his discoveries, perhaps, were the bones and tusks of several species of buffalo, elephant, and rhinoceros, which had long ago disappeared from the frozen Siberian wastes. In some cases the skin of these extinct creatures was preserved, and on it an abundance of hair, from which Pallas inferred that the Siberian elephant and rhinoceros, unlike those living today, were fitted to live in regions where long, cold winters were customary. He also made important observations on the origin of mountain chains. He saw that the highest parts of the Ural Mountain chain, along the axis, consist of the oldest rocks — granites, schists, and other igneous and metamorphic rocks — and that the younger rocks occupied positions on the sides of the chain. He believed that the primitive ocean had never covered the cores of mountains, that it had never stood more than a hundred fathoms higher than at present, and that mountains had been heaved up by volcanic force. While many of the explanations of Pallas were erroneous, he was one of the best observers that natural science has ever had.

To Horace Bénédict de Saussure (1740–1799), a Swiss geologist of note, we owe much of our present-day knowledge of mountains, particularly of the French and Swiss Alps. Saussure recognized the succession of formations and fossil horizons in the rocks of the mountains about his home at Geneva, and the disturbance that the original horizontal strata of the Alps must have undergone. He realized the effects of erosion in sculpturing mountain scenery, and made experiments to determine the origin of certain kinds of rocks. Best of all, he dearly loved the mountains and helped materially in breaking down the prejudice which most men of his day held concerning them. Instead of dangerous places to avoid or to view from a distance, Saussure showed them to be of endless charm, with their varied scenery and interesting wild life. Saussure and Jean André Deluc, a great traveler and observer, in papers dated in 1779, were the first to use the term *geology* to take the place of *cosmology*, which previously had been used to denote the science that treats of the earth and its history. Henceforth the term *geology* was commonly applied to the study of the history of the earth and its inhabitants.

The greatest development in the so-called Heroic Age of Geology was the growth of geological chronology. We have seen that only a few writers had realized that the rocks of the earth's crust told a story of a sequence of events. Buffon, Guettard, Pallas, Saussure, and others believed that the earth had passed through a long series of changes, but the vast bulk of fact necessary to an understanding of the details of the successive stages was slow in accumulating. Arduino (whom we have mentioned as an enthusiastic fossil-collector) had divided the rocks of northern Italy into Primitive (schists and gneisses in the cores of mountains), Secondary (limestones, shales, and other sedimentary rocks with fossils), Tertiary (detritus made from the weathering of older rocks and sometimes full of the remains of fossil land plants and animals), and

Volcanic (lavas and tuffs formed by many eruptions and rearranged by inundations of the ocean). It is interesting to notice that despite the vicissitudes which have beset the nomenclature of geology, Arduino's first three great groups have remained much as he conceived them.

Johann Gottlob Lehmann (died 1767), like Arduino, had seen a natural threefold division in the rocks of the Harz and the Erzgebirge. About the same time, Georg Christian Füchsel (1722–1773) published accounts of the succession of strata and their fossils in the Thüringer Wald, Germany. The work of these two men, in the words of Sir Archibald Geikie, "brought forward clear and detailed evidence that the materials of the terrestrial crust had not been thrown down at random, but succeeded each other in a certain definite order, and contained a record of former processes and changes, like those in progress now."[1] Because of the unattractive manner in which the ideas of Lehmann and Füchsel were expressed, their importance was not immediately realized. The science of geological chronology languished until the coming of a man whose importance in the history of geology is far greater than any mentioned thus far. This man was Abraham Gottlob Werner.

Abraham Gottlob Werner (1750–1817) was professor of mineralogy at Freiberg. The unrivaled leadership he gained over the domain of natural history came from his eloquent skill as a teacher and the inspiration with which he fired his students to undertake the study of nature in an exact, scientific manner. For a man who bulks so large in the development of science, Werner wrote surprisingly little. His reputation was built almost entirely upon his spoken word. His dislike for writing was so great that, as Cuvier relates, the letter which was to inform him of his election to a foreign membership in the French Academy was left unopened and unanswered. Owing to the power of his personality he drew students to him from the four quarters of the globe, until Freiberg became the acknowledged center for the study of earth sciences.

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[1] Archibald Geikie, The Founders of Geology (1905), p. 200. Reprinted by permission of The Macmillan Company.

Perhaps the most outstanding trait of Werner's mentality was orderliness. Since his chief devotion was to the study of minerals, which was then in a state of chaos, his passion for order proved an inestimable boon. The same punctilio with which he arranged a dinner for his friends or the books in his library, he used in placing the minerals in his cabinet. Nor did he stop here, but proceeded to arrange the crust of the earth in a series of "formations." He described the variety of rocks, the details of their position and structure, their succession, as well as their economic value. Werner's system of rock succession was simple because his actual observations were restricted to a small area in Saxony and Bohemia. He taught that the formations which he distinguished in this district could be recognized anywhere in the world, that they occurred in the same order and possessed the same characteristics everywhere. Like most other attempts to simplify complex problems, Werner's chronological scheme succeeded merely in becoming ridiculous. Geikie remarks in this connection that "never in the history of science did a stranger hallucination arise than that of Werner and his school, when they supposed themselves to discard theory and build on a foundation of accurately ascertained fact. Never was a system devised in which theory was more rampant; theory, too, unsupported by observation, and, as we now know,

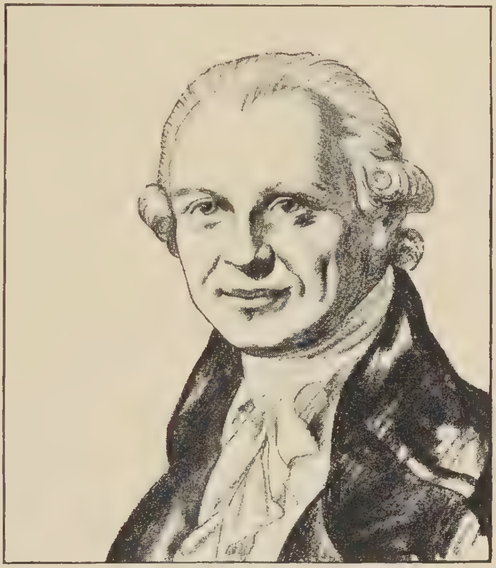

FIG. 243. Abraham Gottlob Werner

utterly erroneous. From the beginning to the end of Werner's method and its applications, assumptions were made for which there was no ground, and these assumptions were treated as demonstrable facts."[1]

One of the greatest absurdities of the Wernerian doctrine was the belief in a universal ocean out of which all the formations of the earth had been precipitated. How this ocean could have held all the rocks in solution, and how the successive deposits were caused to be precipitated, was never explained. Furthermore, Werner disregarded the observations of Pallas and Saussure regarding the structure of mountain chains, and held the sorry belief that all sedimentary rocks had been laid down in the positions they now occupied, whether horizontal or inclined at an angle of 60°. He entirely ignored the evidence for crustal disturbance. Despite the long and careful researches of Guettard and Desmarest on the nature of vulcanism and the origin of basalt, the Wernerians summarily dismissed the conclusions of these investigators and announced an aqueous origin for basalt. They believed that volcanoes arise from the combustion of seams of coal. All these unfortunate doctrines were promulgated far and wide by Werner's enthusiastic students. We shall see with what success they met in spreading the ideas of their great but misguided master.

Leopold von Buch (1774–1853) was the most distinguished of Werner's many students and one of the most illustrious geologists Germany has ever produced. He was one of a large group who went forth to proselytize for the cult of Wernerianism. He proclaimed the orthodox beliefs of Werner regarding the aqueous origin of all rocks. His faith in his master, however, must have received a jolt when he visited the old volcanic region of central France and became convinced of the volcanic origin of the basalt rock in that region. He was loath to admit that what he had learned from Werner about the chemical precipitation of all the rocks of the earth's crust was wrong; so while admitting the obvious volcanic nature of the basalts at Auvergne, he stoutly remained loyal to the Wernerian belief in the aqueous origin of the basalts in Saxony. Von Buch's demonstration of the proofs for recent slow uplift in Scandinavia was a notable achievement in geological science. He recognized, likewise, the paroxysms of disturbance which the mountains of Switzerland and Italy had suffered. He produced the first large-scale geological map of Germany in 1824. He enriched the literature of vulcanism by his researches in the Canary Islands and described many species of fossils from central Europe. When he began his studies he was a strict adherent of the school who followed Werner in the belief in the aqueous origin of all rocks. The geologists of this school were known as Neptunists, and were vigorously opposed by those who saw in vulcanism the important factor in earth history. Von Buch's emancipation from Wernerian misinformation was slow, but gradually he came over to the ranks of the Vulcanists. A great step in this metamorphosis was accomplished when he became convinced that the higher mountains of Europe had never been covered by the sea, as postulated by Werner, but had been elevated by successive uplifts. Von Buch touched every phase of geological science, and was justly considered the greatest geologist of his time.

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[1] Archibald Geikie, The Founders of Geology (1905), p. 212. Reprinted by permission of The Macmillan Company.

Many other students of Werner might be mentioned—many who were slow in altering the absurd Neptunist doctrines of their master and helped to prolong the battle between Neptunist and Vulcanist over the origin of basalt long after the controversy should have been concluded. Others, like Von Buch, came to a realization of the importance of the internal heat of the globe in shaping the destiny of this planet. Without dwelling on the details of this controversy or on the many truths that were brought to light during its progress, let us turn at once to the man who settled the question for all time and brought geology to a state of advancement which might be called modern.

THE BIRTH OF MODERN IDEAS CONCERNING THE EARTH

While the followers of Werner were clamorously spreading their Neptunist doctrines over most of the civilized world, a private citizen of Edinburgh was thinking over the problems so blatantly and incorrectly answered by the enthusiastic crusaders from Freiberg. This man was James Hutton (1726–1797), whose book "Theory of the Earth," one of the finest classics in all geological literature, sounded the death knell of Wernerianism. Hutton was trained in the schools of his native city for the profession of medicine, but he never practiced his profession. Always animated with a keen interest in chemistry and a fondness for rambles in the beautiful country around Edinburgh, he lived for a time as a farmer, until success in an industrial venture made it possible for him to retire from active business and devote himself to some of the scientific problems which interested him. Many of the friends who surrounded him in Edinburgh were distinguished in the several sciences; his walks in the environing country stimulated him to inquisitiveness; his early delight in studying rocks and the surface features of the earth's crust steadily grew. It is no wonder that his active mind turned to the consideration of geological problems. Urged by his learned friends to publish his ideas, he finally did so in 1788. The final statement of his beliefs was not put into written form until 1795, two years before his death.

FIG. 244. James Hutton

The guiding rule in Hutton's philosophy was that past events in the history of the earth must be interpreted in the light of what is happening today. He believed that the present alone could unlock the secrets of the past, and, unlike the speculative cosmogonists, he looked directly to the earth for a solution of the problems of its history. He had throughout his life the true scientific attitude — an open mind for all unsolved problems — and not, like Werner, preconceived beliefs with which he attempted to harmonize the facts of nature. He saw that the earth had not always worn its present aspect, that it had passed through a long history of varied changes. He saw that accessible parts of the earth's crust were composed of sandstones, conglomerates, shales, and limestones disposed in layers very similar to the layers now accumulating in all lakes, seas, and oceans. He distinguished also an older set of rocks, such as granites, which normally lay below the sedimentary rocks. These he called *primary*. The sedimentary rocks, obviously derived from older formations, he called *secondary*. He believed that subterranean heat caused the loose sediments in the ancient sea bottoms to be hardened into the rocks which comprise the secondary group, and he made experiments to determine the effect of heat on various kinds of sediment. Hutton believed that sedimentary rocks found high above the present ocean level had been lifted by upheaval, and not, as the Wernerians insisted, deposited in place from a universal ocean. He saw correctly that earth movements came at different times, and he read from the study of the rocks themselves a consecutive story of the earth. Although many of the facts expressed in Hutton's famous book were well known, he was the first man in the history of geology to paint the picture of the earth's history as a logical connected whole. He described the slow destruction of land surfaces by the tools of erosion, the physical and chemical methods of denudation. He emphasized the vastness of geological time. As Geikie says, "The whole of the modern doctrine of earth-sculpture is to be found in the Huttonian theory." He disproved Werner's absurd belief that granite was a precipitation from sea water, and proved the igneous nature of it and similar rocks. He demonstrated the metamorphosis of sedimentary rocks which had been invaded by igneous intrusives.

Throughout Hutton's "Theory" the inductive method of reasoning alone is used. He made the earth tell its own story. He saw the balance which exists between erosion and deposition: that just as an old land surface is worn away, materials for new lands are laid down; that, in his own words, "we find no vestige of a beginning, — no prospect of an end." He established all the fundamental truths of physical and dynamical geology.

Hutton's splendid mind and his unselfish and happy personality won for him friendships among the leading scientists of his day. Two of these were of particular importance in the history of geology. John Playfair, the distinguished mathematician and physicist, was intimately acquainted with his friend's geological views, and in 1802 wrote "Illustrations of the Huttonian Theory," in which Hutton's beliefs were better expressed than by his own pen. For clearness, logic, precision, and charm of expression Playfair's writing is excelled nowhere in scientific literature. Through his "Illustrations" the principles of the Huttonian theory were fixed lucidly for all time and secured for Hutton an unequaled eminence among the pioneers of geology.

Sir James Hall (1761–1831), another intimate friend of Hutton, deserves a high place among the pioneers of geology because he proved that experimentation could be used to aid in the solution of certain kinds of difficult problems. He gathered specimens of lava from Vesuvius and Etna, melted these, and arrived in each case at the same result. The lavas fused to an amorphous glassy mass. Hall was firm in the opinion that crystallized rocks, such as granite, were derived from materials in a liquid condition, as Hutton had postulated. By continuing his experiments he found that by regulating the rate of cooling in his rock melts he could produce rocks whose texture ranged from finely crystalline to coarsely crystalline. Hutton had never been attracted by the possibilities of experiment: he believed that the processes of nature were too complicated and on too large a scale to be successfully imitated in the laboratory. When Hall succeeded in producing crystalline rocks from an igneous melt in his laboratory, he substantiated the field interpretations of his friend and drove the last nail into the coffin of Werner's idea that crystalline rocks in all cases had been precipitated from sea water.

Hall did not stop here, but set out to prove experimentally some of the other important doctrines of Hutton. One of these was the belief that the effect of heat on any rock is influenced by the pressure sustained by the heated rock. He devised apparatus wherein chalk could be heated in sealed tubes under the great pressures developed by the imprisoned air and carbonic-acid gas derived from the heated chalk. In this way the chalk was fused without the loss of its volatile constituents, and a substance closely resembling marble was the result. Thus Hutton's belief in the metamorphism of rocks by combined heat and pressure was proved in his friend's laboratory, and another kind of crystalline rock was produced by other means than precipitation from solution.

Hall made further experiments on the folding of rock strata. The machine devised in his laboratory for contorting layers of cloth and clay and producing in miniature the types of rock deformation to be observed on such a gigantic scale in nature was the first of its kind, and still stands as a model for similar devices today. Altogether, the experiments of Sir James Hall surrounded the Huttonian theory with the strongest sort of fortifications. False beliefs die hard, however; and the more convincing the proofs adduced by the Vulcanists, the more doggedly did the Neptunists fight. The struggle of the Wernerians, after the epoch-making researches of Hutton, Hall, and Playfair, was the death spasm of the misguided Neptunist school, although the protagonists in their enthusiasm did not realize it. The decay of Wernerianism was henceforth sure and rapid, and with its disappearance came a new era in the history of geology.

THE RISE OF MODERN STRATIGRAPHY

Just as the eighteenth century saw the cessation of weird speculation about the origin of the earth, so the nineteenth century witnessed a careful revision of beliefs concerning the successive events of the earth's history. The long battle between the Vulcanists and the Neptunists had cleared the scientific atmosphere for the introduction of correct methods in reading the testimony of the rocks by showing the folly of such arbitrary doctrines as those of Werner and by demonstrating that only from a study of the earth itself, interpreted in the light of processes now active on the globe, can the past events of its history be ascertained.

Some of the earlier students of the earth's crust — notably Martin Lister, Lehmann, Füchsel, and a few of the Italian scholars — realized that in the strata of the earth's outer shell was concealed a story of change covering countless ages of time. They saw that through the fossils contained in such strata a connected history of the earth might be had. The true significance of the stratigraphic succession of formations was only partly realized until the coming of an Englishman who more than any other may be said to have founded this branch of the science. This simple man, with a simple name, is known as the Father of English Geology, and stands out as a mountain in the vista of earth science which our retrospect calls forth.

William Smith (1769–1839) came from a humble home and was self-trained to the profession of surveying. In the course of this work he became interested in the succession of rocks and soils in different parts of England, and soon realized that the stratified sedimentary rocks held different assemblages of fossil shells by which they could be identified wherever found. His work as a surveyor took Smith back and forth throughout England, with the result that he acquired a thorough knowledge of the rock structures of his native land. For many years his notes grew, but the leisure to prepare them for publication seemed never to present itself. The scientific world was unaware of his activities until 1799, when, through the help of two friends, he drew up a "Table of Rock Strata" from the Coal Measures to the Cretaceous chalk formations of England. Although the table was not published, it was circulated by Smith's friends among the scientific men who might be interested. It commanded immediate attention, because in it Smith had worked out alone the fundamentals of stratigraphy and had applied them to the rocks of England in a way that was utterly original. Each important sedimentary formation was identified by the fossils peculiar to it, and in this way was traced in its outcroppings over the length and breadth of the country. Nobody had dreamed that fossils could be used in this way until Smith conceived the notion and put it to a practical test.

FIG. 245. William Smith

After long delays Smith realized the impelling ambition of his life in 1815, when he was able to publish his "Geological Map of England and Wales, with Part of Scotland." This map, on the scale of five miles to the inch, represented twenty years of toil on the part of its author. It was the first map to show on such a scale not only the distribution of formations but the stratigraphy as well. This great accomplishment brought Smith immediate fame, as well it might; for it was the production of a simple English yeoman working absolutely alone, without the aid of a university education or access to foreign literature — a production which, to cite the words of

D'Aubuisson, did for the whole of England "what the most distinguished mineralogists during a period of half a century had done for a little part of Germany."

A great impetus was given to the study of stratigraphic geology by the pioneer work of William Smith. The rocks of the earth's crust were arranged in their true time sequence, and fossils from different localities were minutely studied and compared. In France the pioneer work in stratigraphy was done by the Abbé Giraud-Soulavie (1752–1813), the famous evolutionist Lamarck (1744–1829), the great zoölogist Cuvier (1769–1832), and his illustrious associate Brongniart (1770–1847). Such names as the last three hardly need introduction, since they stand for men who are widely known as the great founders of many of our modern conceptions in the fields of biology.

Lamarck (who began his scientific career as a botanist, but later turned his attention to zoölogy) deserves the title of "Founder of Invertebrate Paleontology" which was given him by Sir Archibald Geikie because of his work "Animaux sans Vertèbres." In this work he urged the study of fossil shells in comparison with living forms, and restricted the word "fossil" to organic remains. Literally the word means "something dug up," and literally it has been applied to everything from minerals and buried necklaces to shells and bones of animals. Even as late as the present century in the literature of geology have occurred references to "fossil sand dunes," "fossil ripple marks," and the like, although the best usage follows Lamarck in considering as "fossil" only such remains of animals and plants as have been buried for a long period by natural causes. Lamarck was the first to emphasize that while the majority of fossil types belonged to marine creatures, some lived on the surface of the waters, some at intermediate depths, and some on the bottom. He interpreted the nature of the creatures' former habitats from a study of their remains. He realized that the species of plants and animals were not permanently fixed in time but subject to change under varying conditions of environment. The change of hereditary lines under varying environment was the thesis to which Lamarck dedicated the finest thought of his long life. Perhaps the most philosophical scientist of his time, he goes down in history as the first great proponent of the doctrine of organic evolution.

Cuvier did for the science of vertebrate paleontology what Lamarck did for invertebrate paleontology. He was the first to describe the fossil mammals from France, — the first fossil mammals to be made known to science. Many other kinds of fossil bones were made to live again by the clear and vivid pen of Cuvier. He emphasized the necessity of comparing fossil animals with those living today. By so doing he found that many of the modern forms are very different from their earlier brethren and that others agree more closely but now live under entirely different environmental conditions. Cuvier raised the study of comparative anatomy to the dignity of a distinct science. In this narrative we dismiss him briefly, because his work only remotely touches the field of geology; but he stands today as one of the great men who have glorified the history of science.

Alexandre Brongniart, friend and associate of Cuvier, was an able student of fossil remains and, with his illustrious friend, was the first to make a serious study of the rocks in the Paris basin. He described many genera and species which occurred in the sedimentary formations of this region, and used the similarities among fossils in strata of similar age to trace the various formations across the country. Cuvier and Brongniart published jointly a paper on "The Revolutions of the Surface of the Globe." In this paper it was stated that the earth had suffered periodic revolutions, so sudden, violent, and widespread as to destroy nearly all creatures alive at the time. The successive fossil faunas in the rocks of any given locality were explained as migrations from some other territory where organisms had succeeded in regaining a foothold after each disaster. Cuvier believed, also, that species of plants and animals were fixed, — that new forms did not develop from older types, but that each form resulted from separate and special acts of creation. Because of his strong personality he found plenty of followers to preach these doctrines; and a school was built up, known as the cataclysmists. This school prospered because it had the support of the Church. Was not the Biblical flood easily explained as the most recent of Cuvier's "world catastrophes"? As geological knowledge accumulated, the scientific world began to realize that the great revolutions described by Cuvier had never occurred; and with the epoch-making book of Charles Darwin men began to see that no good proof of "special creation" existed, but that organisms changed slowly through the ages, one type growing out of a preceding type. So it was that the ideas of the cataclysmists, like those of the Neptunists before them, went into the discard.

Despite the erroneous catastrophic doctrine of Cuvier, the influence of the great biologists and geologists of the early part of the nineteenth century in France greatly aided the progress of geological investigation. Like William Smith in England, these French savants realized the value of fossils as datum planes to help the student to unravel the events of the earth's history. From that time to the present, geology has advanced by leaps and bounds.

One of the noteworthy developments in the earth sciences toward the middle of the nineteenth century was the rise of great teachers and the preparation of textbooks of geology. Knowledge was accumulating so rapidly that easily available reference books of a general nature became a necessity to teaching. In the earlier works of this type, particularly the "Lehrbuch der Mineralogie" (1801–1803), by F. A. Reuss, and the "Elements of Geognosy" (1809), by Robert Jameson, the warped attitude of the Wernerian school was strongly in evidence. The transition to more scientific beliefs is shown in J. F. d'Aubuisson's "Traité de géognosie." Similar books were printed in Germany, Belgium, and Italy at this time. In England, W. D. Conybeare and William Phillips published an excellent summary of the geology of England and Wales in 1822. In 1831 H. T. de la Bèche published the "Manual of Geology," which was the first textbook of geology to become of world-wide significance. The original English edition was translated into German and French, and a separate edition was brought out in the United States.

The greatest teacher and writer of textbooks on geology at this time was Sir Charles Lyell (1797–1875). He became the champion of Hutton's doctrines, so that today many of the ideas which originated in the mind of the latter are credited to the former. Lyell's "Principles of Geology" and "Elements of Geology" remain as great classics in the literature of earth science, works which all thorough students of geology must read today.

From the middle of the nineteenth century to the present day, geology has grown with exceeding rapidity. In England Sir Roderick Murchison and Adam Sedgwick, after much heated controversy, resolved the early Paleozoic rocks of Great Britain into the Cambrian, Silurian, and Devonian systems. The Geological Survey of Great Britain, inaugurated in 1835 by La Bèche, carried on the work for which it was founded, which was to depict the geology of Great Britain on detailed maps. In France, at the same time, Joachim Barrande described the fossils and correlated the formations of the lower Paleozoic rocks. The work of distinguishing the great periods of deposition and erosion during the Paleozoic was carried on by many earnest students; but the story of how the time scheme of geological events was brought to its present state is too long and too technical to be told here. Let it suffice to say that the work is not yet completed; that the great plan of earth stratigraphy was deciphered before the beginning of the present century, but every year more detailed information is being acquired by scholars all over the world.

During this period of the vigorous enlargement of the science in all its divisions the names of two men stand out among the many investigators devoted to the study of earth problems. These men were Charles Darwin and Louis Agassiz. Darwin (1809–1882) in his "Origin of Species" revolutionized the thinking of the civilized world by demonstrating in simple language the colossal bulk of the evidence for organic evolution. In the same work he had two chapters on geology which were destined to influence profoundly the trend of subsequent geological thought. In these chapters Darwin pointed out that the interval between any two formations may represent a far longer time than the formations themselves. He showed that the living creatures in the first fossiliferous formations were highly developed, and that many millions of years must have been required to evolve such diversified and specialized types from the primitive ancestors which must have existed before. In fact, all the long ages which have passed since the first fossiliferous formations were deposited have not witnessed as much change in living things as the time which preceded these earliest rocks with fossil remains. The early history of organisms is shrouded in darkness because no traces of animate beings are to be had from the oldest rocks in the earth's crust. Nevertheless, if the doctrine of evolution is true, the changes wrought in the primeval protoplasm to produce the highly organized crustaceans of the Cambrian period were more significant than the many changes which followed this period and which finally led to the evolution of the mammals and ultimately to man. Although the antiquity of the earth had been in a measure realized before, Darwin was the first to elucidate the great length of time required for primitive types of plants and animals to develop into the relatively highly developed forms which occur in the oldest sedimentary rocks.

Agassiz (1807–1873), a European by birth, spent the last twenty-seven years of his life in America. When still a young man he distinguished himself by his brilliant work on fossil fishes. As the founder of the modern school of glacial geologists he took his place among the leaders of geology in America, and we shall refer to him again in connection with the rise of the science in this country.

THE DEVELOPMENT OF GEOLOGY IN AMERICA

The continent of North America is ideally constructed for the study of geology. In the great thickness of its sedimentary formations and their undisturbed positions throughout wide areas, North America was destined to throw fresh light upon many moot points in European stratigraphy. The first work on

American geology was done by J. D. Schöpf, a German surgeon who came to America during the Revolution and traveled extensively through the Eastern states. He published the results of his observations in 1787 in Germany. In this work Schöpf noted that the flat coastal-plain region extending from New Jersey to Florida is separated from the hilly country to the northwest by a double series of waterfalls in all rivers flowing into the Atlantic. This was the first printed recognition of the famous "fall line" of the Atlantic seaboard.

Thomas Jefferson was actively interested in geology while he was president of the United States, and under his direction fossil mammal bones were collected in large numbers from Kentucky and Virginia. He established a paleontological room in the White House, and through his patronage must have stimulated a wide interest in fossil collections, although his individual contributions to the knowledge of the earth were not important.

The first notable publication on American geology was William Maclure's "Observations on the Geology of the United States," brought out in 1809. In this work was a colored geological map of the country east of the Mississippi, which won for Maclure the title of "Founder of American Geology." He divided the rocks into four stratigraphical divisions, coloring each division differently, and thus made the ground plan upon which the growing structure of American stratigraphy was to be built. Maclure was the undoubted leader of early American geology. Although his conclusions have been so thoroughly revised and extended with the growth of knowledge as to be unrecognizable today, he deserves a high place as a pioneer in science in a new country.

Benjamin Silliman was the first great American teacher of geology. In the beginning of the nineteenth century several scientific journals were founded which were foredoomed to early death. Silliman is remembered principally for having founded, in 1818, the *American Journal of Science,* a periodical devoted to geology and the physical sciences, and still enjoying a vigorous and healthy existence. Silliman, because of his great influence as a writer and teacher, although his own researches were rather limited, did more than any other man of his time to advance the science of geology.

Under Silliman's influence Amos Eaton in 1816, at the age of forty, abandoned the profession of law for that of geology. He was destined to become one of the pioneers of that science in America and soon demonstrated his great talent and indomitable energy by publishing the "Index to the Geology of the Northern States" in 1818. This work, although influenced by the Neptunist doctrine of Werner, added much to the current knowledge of American stratigraphy.

As in Europe, so in America the progress of science was retarded by the mistakes of its leaders; in fact, the erroneous beliefs of the Neptunists and the cataclysmists were reflected in the ideas of early American geologists. In 1822 an account of the finding of human footprints in limestone rock near St. Louis was published. Some thought them to be the footprints of Christ. Many of the leading scientists of the day ventured opinions as to their origin, and the question whether the impressions were natural or artificial was long and hotly debated. The marks consisted of two impressions of human feet with no tracks leading up or away. One wonders why the obvious explanation that the footprints were carved in the rocks by Indians was so slow in being accepted. Incidents of this type occurred in many countries during the early years of the growth of earth science; they demonstrate the childlike credulity to be found at times even among scientific observers.

The growth of geology in America was rapid between 1820 and 1830. We cannot dwell upon the individual work done, except to mention those men who towered high above their colleagues. The period was dominated by the personality of Amos Eaton, whom we have already mentioned, and Jeremiah Van Rensselaer, who was famed as a teacher. Edward Hitchcock was the first man to do any thorough geological work in the New England region, and Elisha Mitchell the first in the Appalachian Mountains. The highest peak east of the Rockies was named in honor of Mitchell.

In 1830 the state of Massachusetts organized a geological survey, an example followed by Tennessee and Maryland in 1831; by Connecticut, New Jersey, and Virginia in 1835; by Maine, New York, Pennsylvania, and Ohio in 1836; by Delaware, Indiana, and Michigan in 1837; and by New Hampshire and Rhode Island in 1839. With time more states instituted surveys, until today only a few are without some organized body devoted to the gathering of geological data.

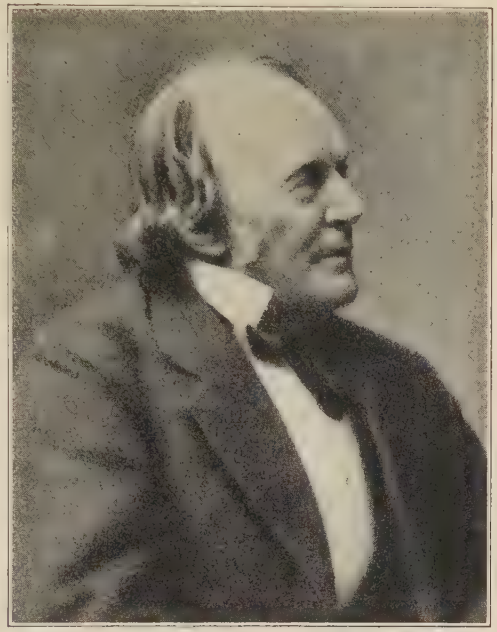
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FIG. 246. Louis Agassiz

The early days of official geological investigation were signalized by the work of Henry D. Rogers and his brother, William B. Rogers. The former was professor of geology in the University of Pennsylvania, and also state geologist. He was the ablest structural geologist of his time, as well as a lucid and stimulating speaker. His brother William did for Virginia what Henry did for Pennsylvania. He was a pioneer in the study of the structure of the Appalachian region, and a skilled orator as well. The task of pushing the frontier of geology westward continued, David Owen in Indiana and Douglas Houghton in Michigan accomplishing works of outstanding merit. No great contribution to world geology was made, however, until Louis Agassiz in 1840 proposed his glacial theory. He was the first man to assign a glacial origin to the drift of loose sand, gravel, and bowlders which cover most of northern North America, Europe, and Asia. Although his theory was slow to be accepted by his contemporaries, no one doubts the truth of it today.

Credit for the elucidation of the older pre-Cambrian rocks of North America falls largely to the great Canadian geologist William E. Logan (1798–1875). Although Maclure had long before recognized the ancient schists and gneisses of the basal complex, and Eaton the old gneisses of the Adirondacks, Logan, at the head of the young Geological Survey of Canada, was the first to point out the great unconformity which exists between these old metamorphics and the earliest fossiliferous formations. He was the first to study pre-Cambrian rocks in detail and to throw light upon the most obscure problem in all geological science.

The work of describing and mapping the geology of the United States continued under the direction of state surveys and individuals working independently. The Federal government took a hand by the middle of the nineteenth century, and great reconnaissance surveys of large areas in the West were made. The names of J. S. Newberry, Clarence King, F. V. Hayden, and J. W. Powell are illustrious in this connection. In 1879, when the government found that some of these expeditions were covering the same ground, all geological work was combined under the direction of the United States Geological Survey, an organization which has continued its splendid exploratory work with unabated zeal to the present.

With the organization of the United States Geological Survey came the development of that branch of geology which deals with the application of the science to the practical service of mankind. Notable among the early contributions of the survey to economic geology were the investigations of the great iron and copper ores of the Lake Superior district and the various reports on the metalliferous deposits of the Far West. This type of work received its initial impetus during the closing years of the nineteenth century, largely through the energy and intelligent enthusiasm of S. F. Emmons. It has been ably carried on to the present by a large group of competent men under the leadership of J. F. Kemp and Waldemar Lindgren. The development of economic geology was largely made possible by the development of the petrographic microscope and the information which this instrument imparted concerning the structure and origin of the various igneous-rock types. Under the leadership of the great German investigator Rosenbusch the science of petrography made great headway at home and abroad. Through the microscopic study of the metalliferous ores and the rocks with which they are associated, economic geology was put upon the firm foundation of scientific fact which it occupies today.

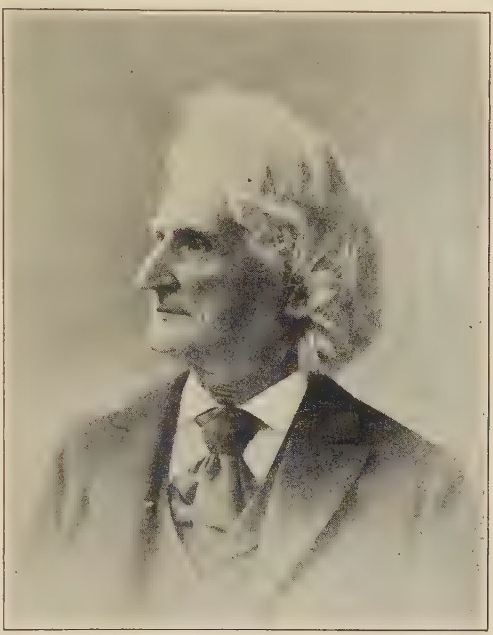
FIG. 247. James Dwight Dana. (Courtesy of Dr. Edward S. Dana)

The careers of two other men should be mentioned in even the briefest account of the history of geology in the United States, namely, J. D. Dana (1813–1895) and his contemporary James Hall (1811–1898). Dana is best known for his "System of Mineralogy" (1837), a classic in the literature of geology and accepted as the most authoritative textbook of mineralogy the world over; his "Manual of Geology" also became a standard work of a general nature. He showed his versatility in his great work on "Corals and Coral Islands" and in his studies toward solving the problems concerning the uplift and depression of continents. Dana truly deserved the title of "foremost American geologist." James Hall did more to elucidate the extinct organisms of the Paleozoic rocks of eastern North America than any other investigator. His long service with that finest of all state geological organizations, the New York Museum of Natural History, and its sister organization, the New York Survey, bridged a period of over sixty years.

One notable development in North American geology which must receive at least passing mention is the discovery and the description of great quantities of the bones of fossil vertebrates. This work was done largely through the efforts of five men: Joseph Leidy, O. C. Marsh, E. D. Cope, and, later, Samuel Williston and H. F. Osborn. Much information concerning the evolution of backboned animals resulted, and the work of these Americans stands with the best of its kind ever done.

Perhaps the most distinctively American developments in earth science were the physiographic studies inaugurated by C. E. Dutton, G. K. Gilbert, and J. W. Powell in the arid plateaus of the West, and by W. M. Davis in the East. Largely through the work of these men the theory of erosion cycles and the history of land forms were made intelligible. The interplay of uplift and subaërial erosion had previously been recognized, but American geologists are largely responsible for working out the details of a logically connected history of topographic features.

With the birth of the twentieth century, geology at home and abroad had become so specialized that a single individual could no longer be well versed in all its divisions. Refinements in stratigraphy, the large bulk of fossils described, and the new light shed upon the structure of minerals and rocks by the invention of the petrographic microscope make it difficult to think longer of the science of geology as a unit. The ultimate goal, however, of all the branches of earth science — whether petrography, paleontology, physiography, or any other — is the same: to unravel the history of the earth and its inhabitants. The endeavor of this book has been to show how far the combined efforts of all the divisions of geology have attained to this ideal.

From this brief summary of the growth of earth knowledge the weakness as well as the strength of human minds and hearts has been displayed. What is the lesson to be learned by the present generation? We can conclude in no better way than by giving thought to the comment of Sir Archibald Geikie on our heritage from the past:[1]

> Each of us has in his power to add to this accumulation of knowledge. Careful and accurate observation is always welcome, and may eventually prove of signal importance. . . . Above all, let us preserve the modesty of the true student, face to face with the mysteries of Nature. Proving all things and holding fast that which we believe to be true, let us look back with gratitude and pride to what has been achieved by our forerunners in the race, and while we labor to emulate their devotion, let us hold high the torch of science, and pass it on bright and burning to those who shall receive it from our hands.

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[1] Archibald Geikie, The Founders of Geology (1905), p. 473. Reprinted by permission of The Macmillan Company.

CHAPTER IX

GEOLOGY IN THE SERVICE OF MAN

Of the many descendants of the great parent science of geology, one more than any other deserves our special consideration. This offspring is sometimes called economic geology and sometimes applied geology. As its name betokens, this child of earth science is dedicated to the betterment of man. In a narrow sense economic geology deals strictly with the mining industry and concerns itself with the problems of occurrence, distribution, origin, and extraction of mineral deposits. In a broader sense economic geology devotes itself to a highly varied group of problems encountered by mankind in wresting from the earth the physical necessities of life and comfort. In a still larger sense those phases of geological science which aid in deepening the insight and broadening the mental life of men can be truly said to have an economic or applied value. Our purpose in this chapter will be to inspect the practical side of geology from this broad point of view.

GENERAL SCOPE OF GEOLOGICAL SERVICE

Certain official organizations in all countries are fundamentally devoted to utilitarian geology, and draw their sustenance from the people they serve. The Federal organizations of the United States are the paragons of such bodies among the great nations of the world, and the models which many of the states have copied on a smaller scale. The United States Geological Survey stands preëminent among the organizations devoted to practical geology, and the Bureau of Mines, the Weather Bureau, and the National Museum, although working in more limited fields, are none the less efficient and enthusiastic in their service.

The United States Geological Survey was instituted purely for the public service, to prevent the waste of natural resources and, in the words of Congress, to place "the work of national development and the elements of future prosperity upon the firm and enduring basis of truth and knowledge." By bulletins on the special geology of limited areas, by monographs and professional papers on larger problems of a more general nature, by papers on the water supply, and by annual reports on the mineral resources of the United States (now published by the United States Bureau of Mines), as well as in many other ways, the Federal survey has well justified its existence.

One of the most ambitious and worthy tasks of the United States Geological Survey is the preparation of a complete topographic atlas of our country and its possessions. As the work on this great map (begun in 1882) has proceeded, completed portions known as *quadrangles* have been published from time to time. Each quadrangle is bounded by parallels and meridians and is printed on a sheet approximately $16\frac{1}{2}$ inches by 20 inches. Most of these quadrangles depict an area 30 minutes each way on a scale of about two miles to the inch. Areas of important industrial centers are mapped on a scale of approximately one mile to the inch and are published in quadrangles covering 15 minutes. Maps on still larger scales are used in connection with irrigation, drainage, and important mining districts. The smallest scale, four miles to an inch on quadrangles of 1 degree, has been used for desert areas and some other regions in the western part of the country. Most of the quadrangles of the United States Geological Survey are divided along parallels and meridians into *rectangles,* which are divided into *townships,* which in their turn are divided into *sections* (Fig. 248). The section is the standard unit of land division; it consists of a square area one mile on each side.

Topographic maps depict not only such cultural elements as roads and towns and such natural features as lakes and rivers, but also the form of the land surface, or *relief.* In this regard topographic maps differ from ordinary "flat" maps. Relief is usually shown by fine lines drawn through all points of equal elevation. By means of these lines, or *contours,* not only the shapes of hills and valleys but also their elevations are shown

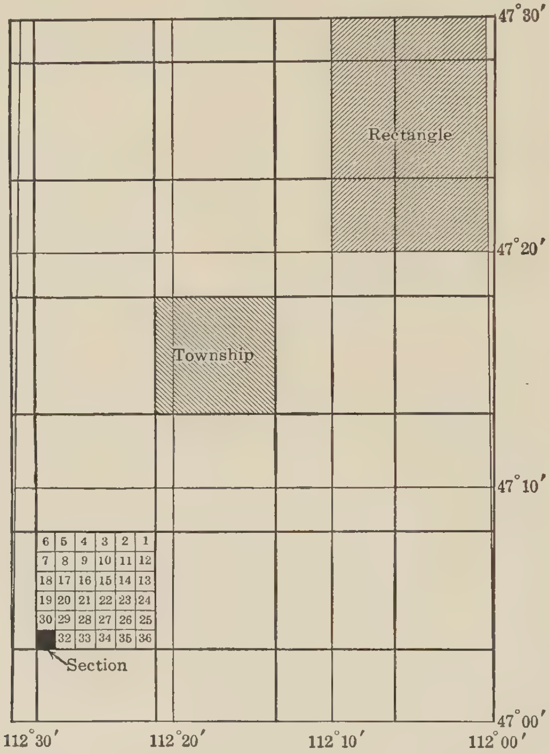

FIG. 248. Diagram of a 30-minute quadrangle of the topographic atlas of the United States, illustrating the smaller subdivisions — rectangles, townships, and sections

(Fig. 249). The vertical interval between contours is stated at the bottom of each topographic map. In a flat country this interval, known as the *contour interval,* may be as small as five feet, and in mountainous regions it may be as great as two hundred and fifty feet. Where successive contours are far apart, a gentle slope is indicated; where they are crowded, a steep slope is depicted. Where the elevation of cliffs and vertical bluffs is represented, the contours are blended into one line.

The practical and cultural value of topographic maps is at once apparent. With a little study any intelligent person can see at a glance the chief features of a land area. Both to the engineer and to the tourist the Federal maps are valuable in many ways. They constitute perhaps the greatest single contribution of the United States Geological Survey to the public good.

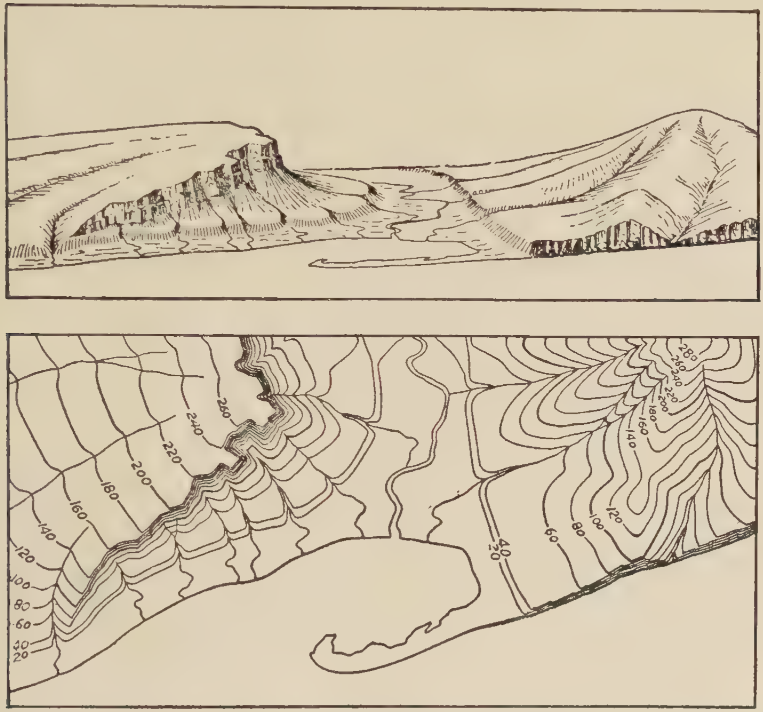

FIG. 249. An ideal view and the corresponding contour map. (Courtesy of the United States Geological Survey)

The Geophysical Laboratory of the Carnegie Institution at Washington conducts many researches important in aiding the progress of man, as do many other foundations and universities. Geology has many times proved its usefulness in great engineering projects, for example, in the building of the Panama Canal and in the water supplies of large cities, notably those of New York and Los Angeles. Many mining and oil companies, as well as some railway companies, maintain a staff of trained geologists, — men who have often proved the practical value of geology by saving their companies large sums of money.

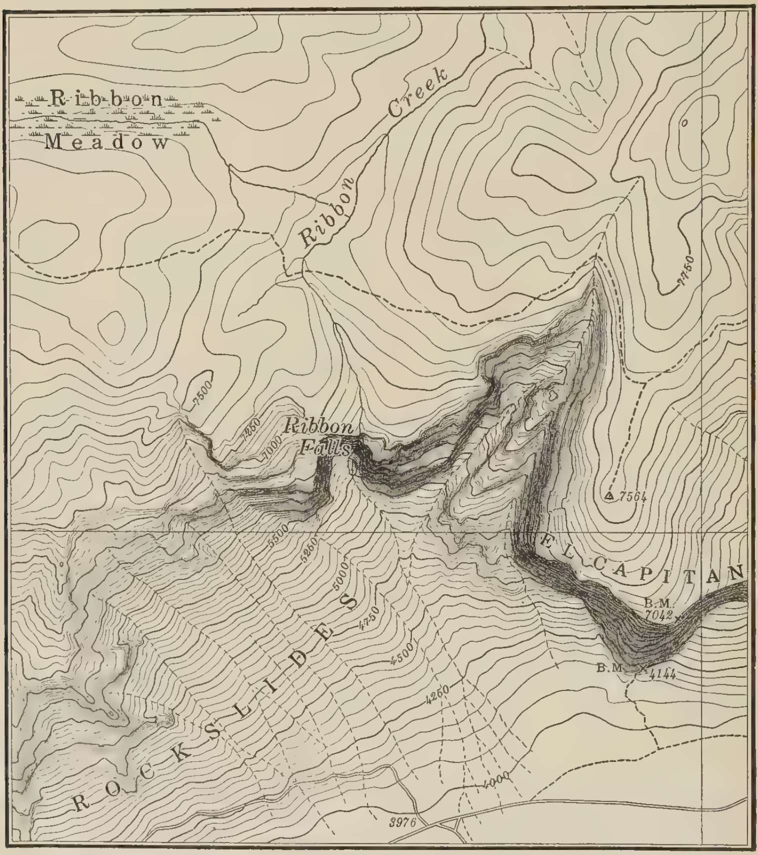

FIG. 250. Portion of a contour map. (Courtesy of the United States Geological Survey)

GEOLOGY APPLIED TO INDUSTRY

Exploration for mineral deposits. A superficial examination of the earth is sufficient to show that nature is not lavish with her mineral treasures. Compared with the great bulk of rock in the earth's crust, valuable mineral deposits are a vanishing quantity. Where such deposits occur they have been concentrated under peculiar and exceptional conditions. It is to these conditions that the economic geologist directs his attention. By studying the geological features of a region which produces valuable minerals in paying quantity, the peculiarities of occurrence of a given type of mineral deposit and the nature of its origin are ascertained. With this knowledge the geologist is prepared to look elsewhere for new deposits of the same type.

The value of geology in exploration was the first of the many practical attributes of the science to be recognized by industry. Since the early years of the present century the great mining companies of the world have become increasingly dependent on geologists for exploratory work. It was not without difficulty that geology established a general recognition of the service it can render in this regard. The world cherishes a traditional distrust for "theory," and the geologist, trained in laboratory technique and informed on many phases of earth science of which the "practical prospector" is ignorant, has been handicapped in establishing the soundness of his judgment in mining matters. Then, too, the well-trained geologist suffers for the mistakes of the undertrained and the charlatans in his profession. All professions suffer in this way; but perhaps none so much as applied geology, since there is a tendency to feel in regard to mineral deposits that one man's guess is as good as that of another. A more pernicious obstacle in the path of the economic geologist is the opposition of dishonest and misguided promoters who feed on the ignorance of a public desirous of growing rich overnight. Realizing the worthlessness of such schemes, the geologist condemns them, and in so doing brings condemnation on himself. Despite these obstacles the geologist has won his place in industry. Today many of the larger mining organizations have taken the important matter of exploration out of the hands of the "practical" explorer and have placed it in the hands of geologists.

Much could be said regarding the exploration of new territory for mineral deposits. Nothing demands the use of more of the faculties of a highly trained intelligence. The geologist fitted for his task brings not only such intelligence but also a knowledge of geology. The problem of locating new mineral resources is largely a problem of eliminating regions where the particular mineral sought is not likely to occur. With his knowledge of the origin and occurrence of mineral deposits, the geologist is clearly best fitted to do this. Since most of the rocky crust of the earth is barren of valuable minerals, it is important to know the conditions under which such minerals occur. Certain ore deposits are found in the contact zone between intrusive igneous rocks and sedimentary rocks. The geologist knows this, and knows how to recognize such a zone when he finds it. After finding it, he knows from previous experience — his own experience or that of other students of ore deposits — where in this zone to look for valuable minerals. The geologist knows that oil occurs in sedimentary rocks of certain ages and structures. Therefore he does not advise drilling into massive igneous rocks in search of the valuable "black gold"; yet each year oil wells are drilled into such rocks on the advice of "practical" prospectors and divining-rod charlatans.

The scope of this chapter permits but the merest suggestion of the value of geology in exploration. It is known that certain deposits are most common in rocks of the same age, and that many deposits are localized in relatively small areas of the earth's crust. In many places valuable mineral deposits outcrop at the surface, and in many such cases the prospector can easily recognize them. In other places the deposits are concealed from view by overlying rock. Here it is that the service of geology is most in demand. By a study of surface conditions, aided in some cases by reconnaissance drilling in areas suspected of hidden treasure, geologists have often brought about the discovery of new mineral deposits. Such was the case in the Junction shaft of the Calumet and Arizona at Bisbee, Arizona, where a concealed deposit of rich copper ore was brought to light through the application of geological principles. Knowledge of the nature and origin of an ore deposit often aids the geologist in prophesying the size and depth of the deposit from a study of the surface outcrop. In this way it can often be foretold whether or not a deposit is worth exploiting. By using magnetic surveys to locate iron ores below the surface, by tracing placers to the "mother lode," by studying climatic and topographic conditions in the search for outcrops of certain minerals, by drilling, but especially by studying the origin of bodies of ore and the nature and structure of the rocks in which they occur, the competent geologist has proved himself invaluable in the exploration for mineral resources.

Geology in relation to coal-mining. Coal is the most valuable of mineral deposits, since it is the most abundant and the most widely used of the energy-producing minerals. We have seen in an earlier chapter that coal originates largely from the decay of plant tissues. The accumulation of coal is essentially a sedimentary process, and all coal seams are associated with beds of sedimentary rocks. The discovery of coal beds is not a difficult matter, since the Carboniferous rocks, in which coal is most abundant, lie at the surface over wide areas, and the coal seams associated with them are easily detected by their size and characteristic appearance.

The geologist's chief service to coal-mining is not in the discovery of coal beds but in their exploitation. Seams of coal have the approximate shape of sedimentary beds, but they are always less continuous and tend to the irregular superposition of one bed on another, with strata of sandstones and shales between. Therefore it is normally difficult for the average miner to follow a coal seam without needless waste. It is here that the geologist, with his knowledge of sedimentation, can often point the way.

Many coal beds show marked structural irregularities induced by deformative movements in the earth after the materials constituting the coal had been laid down. Not rarely coal seams are incorporated with complexly folded and faulted sedimentary rocks. Because of the variations in thickness of the original seams, of the variations in resistance to the stresses engendered by deformation, and of other factors, the problem of following a distorted coal seam may become a Gordian knot which the geologist alone can untie. With his ability to identify and locate minor geological horizons, to follow a given bed through a wilderness of faulted and folded rocks, the geologist can often rediscover a valuable coal bed which had seemed irrevocably lost to the miner. He can do this in an economical way, because in locating the lost seam he uses the evidence of geological structure rather than the wasteful "cut and try" method of indiscriminate excavation. The geologist has taken his place with the engineer in reducing the operating costs of this important industry.

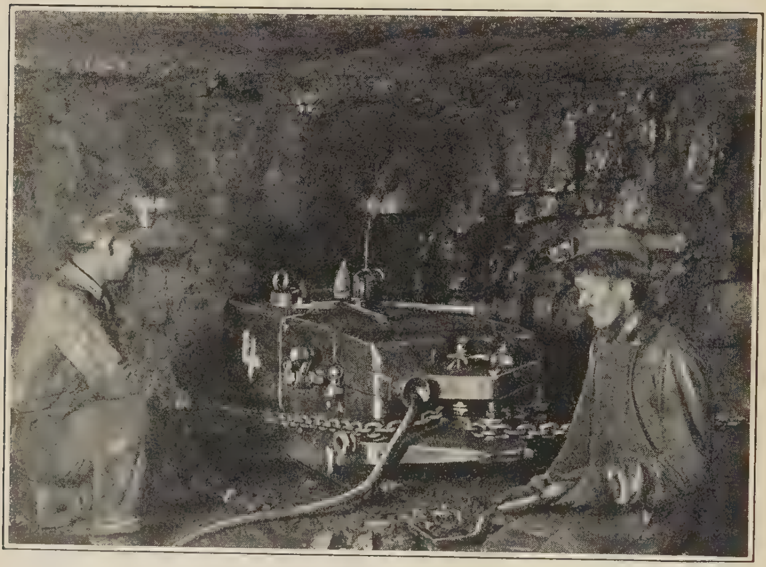
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FIG. 251. Mining in a coal seam with an electric cutting machine

Geology in the search for oil. Petroleum is a close second to coal as a valuable energy-producing mineral. Because of its origin and occurrence, the discovery of oil falls peculiarly within the special province of the field geologist. The petroleum industry offers perhaps the best examples of the application of geological science to the needs of man.

The origin of petroleum. Petroleum is a complicated mixture consisting largely of *hydrocarbons*, that is, various compounds of carbon and hydrogen. Of somewhat similar composition are natural gas, asphalt, bitumen, and related substances.

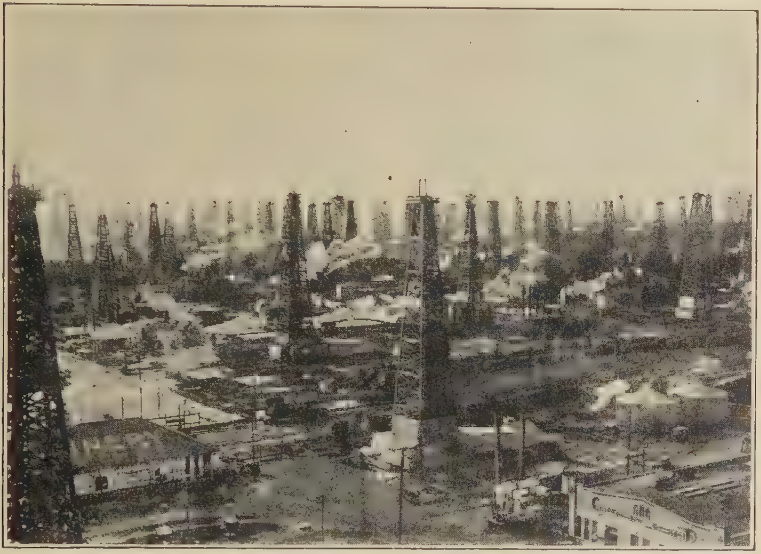

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FIG. 252. A typical scene in a producing oil field

Hydrocarbons are present in nearly all marine sediments, in some fresh-water sediments, and in almost all sedimentary rocks of marine origin. Only under special conditions, however, do they accumulate in sufficient quantity to be of commercial value. It is the duty of the geologist (1) to determine the likelihood of the presence of hydrocarbons in regions not yet tested by the drill and (2) to determine the best location for sinking wells in regions known to possess valuable accumulations. The first can be done only through knowledge of the origin and general occurrence of hydrocarbons; the second, through knowledge of the structural conditions under which hydrocarbons are localized and through the ability to recognize such structures in the field.

Petroleum, which is today the most valuable of the natural hydrocarbons, is always found in association with marine sedimentary rocks. It is generally believed that it was derived from dead bodies of plants and animals deposited with muds and other inorganic débris on the bottom of the sea. Slow bacterial action is thought to free the fatty materials of the decaying organisms. Some of this material volatilizes and escapes to the air; a large portion is thought to rise in the form of tiny globules which attach themselves to fine particles of mud. These ultimately sink to the bottom and become buried under the weight of later sediments. The pressure of these later deposits undoubtedly aids the further distillation of petroliferous material. A striking proof of the organic origin of mineral oils is that under the polarizing microscope they show the same optical properties which characterize animal oils.

The trapping of oil in pools. Since the fatty particles of mineral oil first find lodgment on the sea bottom with particles of mud, it is important in exploring for petroleum in an unproved area to know whether the so-called *mother rock* is present. Such a formation is the consolidated mud of the ancient sea bottom with which the oil globules were deposited. Mother rocks are shale formations blackened by the hydrocarbonaceous materials they contain.

Although black shales are thought to be the parent of all commercial deposits of petroleum, the deposits are rarely found in the mother rock. Under the pressure of ground water the oil globules are dislodged from the carbonaceous shale and forced to migrate upward either under the pressure of gas or under the hydrostatic pressure of the water. Migration proceeds until it is checked by some geological structure. The best structures for the trapping of oil in pools are domes, or anticlines, in the rocks, capped by an impervious shaly bed to prevent the escape of the volatile constituents of the oil to the surface. Here the oil is localized, with the associated natural gas (if present) lying above, and the water which carried the oil to its place of imprisonment lying below. A porous, coarse-grained rock like a sandstone makes the best reservoir for oil accumulation. Petroleum in commercial quantity is usually found in such a coarse-grained formation. The several conditions which in most cases are necessary to the accumulation of a valuable pool of petroleum are diagramed in Fig. 253.

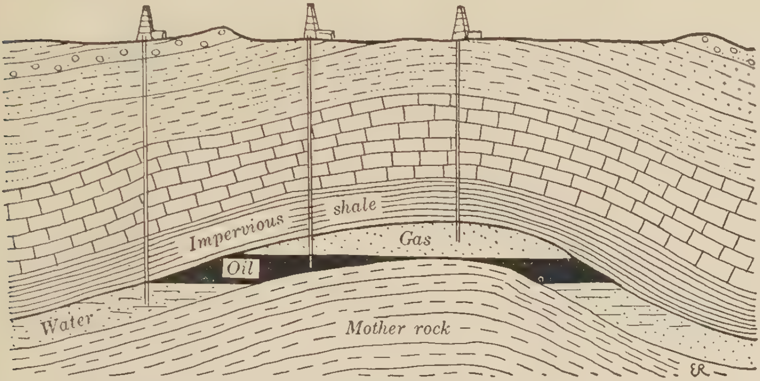

FIG. 253. Diagram showing the conditions necessary for the accumulation of oil in pools

The location of oil pools. The foregoing sketch of the origin and accumulation of petroleum is too brief to indicate the wide range of problems met by the geologist in his exploratory field work. Many structures not mentioned in this account may cause the trapping of oil in pools; many others allow it to seep to the surface and be lost. At every step in the exploration for oil a competent geologist is needed. The stratigraphy of a region must be studied to see in which formations oil is likely to be present. After a locality has been found which appears favorable, detailed maps of the structure of the rocks must be made from a study of their surface outcrops.

In 1885 I. C. White perfected the theory that commercial oil pools tend to be localized on or near the crest of anticlines, and that wells bored into the synclines (which normally alternate in position with anticlines) yield little oil or gas but much of the water associated with most oil pools. This theory, which we have briefly outlined above, is known as the *anticlinal theory*; it has saved the oil industry uncounted millions of dollars. The anticlinal theory, however, is but one example of the service of geology to oil exploitation. Special problems are forever developing, and with these the geologist effectually copes. Most of the large oil companies of the world have realized the value of geology. More geologists are at present employed by oil companies than by any other single industry.

Geology and metal-mining. A course in economic geology ordinarily is concerned with the study of the origin, occurrence, constituency, and shape of the deposits of those minerals which have proved useful to man. Such minerals are largely metallic in nature; when they occur in quantities great enough to be mined profitably, they are called *ores*. The study of ore deposits is one of the largest subdivisions of the science of geology. The scope of this book permits but the merest mention of this subscience because of the technicalities of mineralogy and chemistry which are involved in even a superficial treatment.

Iron is the most widely used of all the metals. Deposits of iron ores are also more abundant than those of any other metal. Formations in which iron minerals are abundant, but not in quantity sufficient to justify mining, outcrop in many parts of the earth. Some of the rich deposits of iron have been concentrated from iron minerals leached out of such lean iron-bearing formations. Most of the valuable iron deposits of the world are of sedimentary origin, and their development can best proceed upon the advice of a geologist who knows the principles of sedimentation and the effects of the various geologic instruments which alter sedimentary formations. Not only the original deposition and concentration of iron minerals but the later deformation of the deposits present problems which often the geologist alone can solve.

Copper is a metal of great importance in the electrical industry and in the manufacture of copper alloys such as brass and bronze. Most commercial deposits of copper are closely related to igneous rocks. A typical copper deposit presents at the surface a weathered zone rich in conspicuous blue and green copper minerals which have resulted from the processes of weathering. Below is ordinarily a rich zone of secondary copper minerals concentrated at and below the level of the

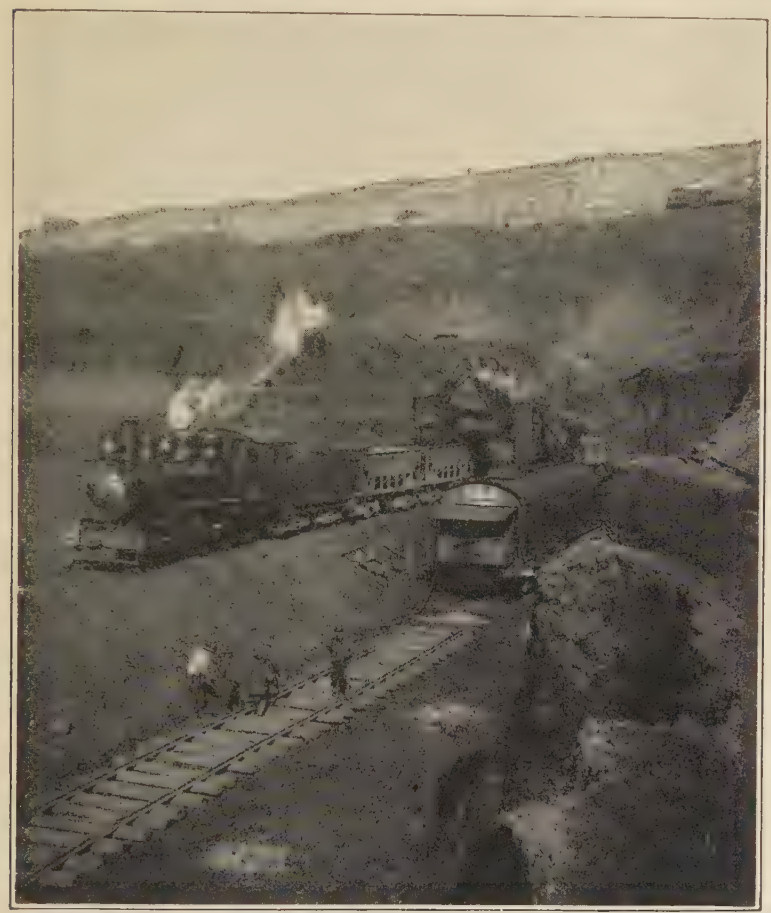

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FIG. 254. Open-pit mining for iron in Michigan

water table from materials leached from above. Below the enriched zone is normally the zone of primary ore, ordinarily of poorer grade, but in some cases very rich. The recognition of the zonal arrangement of copper deposits and the study of the causes of such arrangement have led to a more complete understanding of the genesis of the ore bodies. Needless to say, it is necessary to know the origin of such a deposit to be able to predict its probable size and the probable amount of rich ore it will be found to contain.

Most copper ores are thought to have been deposited from hot solutions ascending through cracks and fissures in the earth's crust from some deep-lying igneous source. These solutions often deposit a variety of valuable minerals. At Butte, Montana, where rich copper ores are found in fissure veins in igneous rocks, the copper-bearing minerals were deposited nearest the igneous source, and lead and zinc minerals were deposited farther away. It is one of the largest divisions of the work of economic geology to study the temperature and other conditions under which valuable minerals are deposited from solutions. In the case of copper the enrichment changes which took place after the original deposition of the ore must also be carefully studied. Finally, the deformation, especially the faulting of the rocks in which rich copper ores occur, must be studied and carefully mapped. The Anaconda Copper Mining Company, operating principally at Butte, maintains a permanent staff of geologists to assist in solving the many problems which must be solved before the ore can be extracted with economy. The underground map of the faults and associated veins of copper ore in the Butte district represents one of the finest pieces of applied geological work ever done.

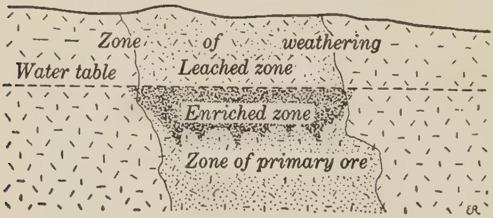

FIG. 255. Diagram illustrating a typical occurrence of copper ore in a vein

The mining of other metals valuable to man depends to a greater or less extent on the direction of competent geologists. Most important among the remaining metals are lead and zinc and the precious metals — gold, silver, and platinum. Of scarcely less value are the ores of tin, aluminum, mercury, cobalt, antimony, arsenic, and bismuth. In all these departments of the mining industry geology plays an important rôle. Many of the geological problems in all mining projects have to do with estimating, with a minimum of excavation, the size, shape, and value of a body of ore. Many have to do with the following of a body of ore where the rocks have been disturbed. On the other hand, each mine has its individual problem for the geologist. Since he brings to the solution of the problem a wide knowledge of conditions in many regions and of many kinds of deposits, he succeeds where often the practical miner fails.

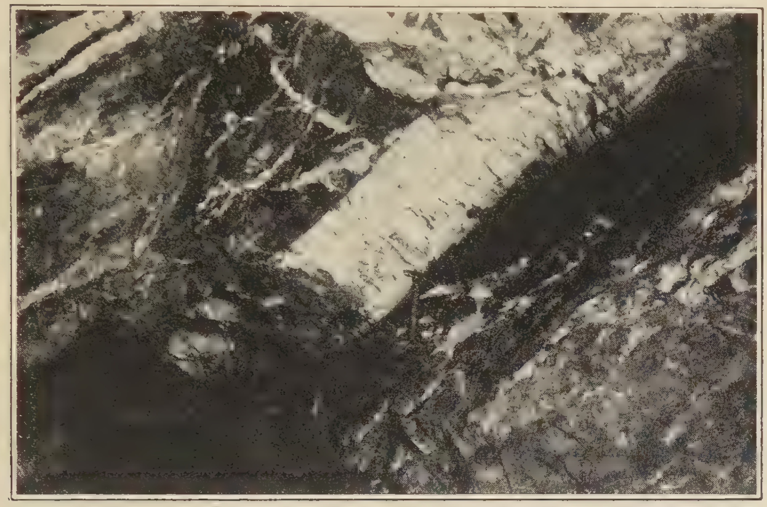

FIG. 256. A gold-bearing quartz vein in California. (Courtesy of the United States Geological Survey)

Geology and the nonmetallic products. We have already made mention of the service of geology to the coal and petroleum industries. Of all the mineral products of the earth, coal and petroleum head the list for the value of the annual output.

Other products of strictly nonmetallic nature, because of their number and ever-increasing yearly value, have made the rocks and minerals of this group of primary importance. In 1890 the ores of the metals produced in the United States equaled the combined value of the nonmetallic products. Gradually the nonmetallic products forged ahead, until in 1924 their annual value was over three times that of the yearly output of all the metals.

None of the other nonmetallic products is as abundant or as valuable as coal or petroleum. On the other hand, there are many which are in steady use and for which there is an increasing demand. Foremost among these are *salt*, used in the preserving and seasoning of foods and in the manufacture of sodium compounds; *gypsum*, used in making plasters; *graphite*, used in manufacturing crucibles, lubricants, "lead" pencils, and many other products; and *barite*, a necessary ingredient in many paints. Of importance, also, are *asbestos*, used in insulating and fireproofing; *borax*, used in the manufacture of borax and boric acid; and *mica*, important in the making of electrical equipment. These and many other products of a similar nature occur in a great variety of ways, and in many cases their extraction from the earth with profit depends largely on the science of economic geology.

An important group of nonmetallic minerals are the *fertilizers*, substances which are taken out of soils by plant life more rapidly than nature can replace them. To make agriculture continually profitable in any given locality these minerals must be replaced artificially. The minerals largely exploited for fertilizer purposes are sodium nitrate, calcium phosphate, and various potassium salts. To a lesser extent lime, sulphur, and gypsum are used as fertilizers. The necessity of using fertilizers is just beginning to be realized, and the fertilizer industry, now in its infancy, is sure to have a great development in the future.

The common rocks of the earth's crust constitute by no means the least important part of the yearly output of the nonmetallic mineral commodities. Among the great variety of rocks with economic value can be mentioned the huge tonnage of materials used in the construction of roads; the great variety of stones used for monuments and buildings; the limestones, used for flux and cement; the slates, suitable for roofing; the clays, made into bricks and pottery. Such materials are handled daily by the geologist, and he is often instrumental in pointing out the true significance and value of deposits previously neglected or incorrectly developed.

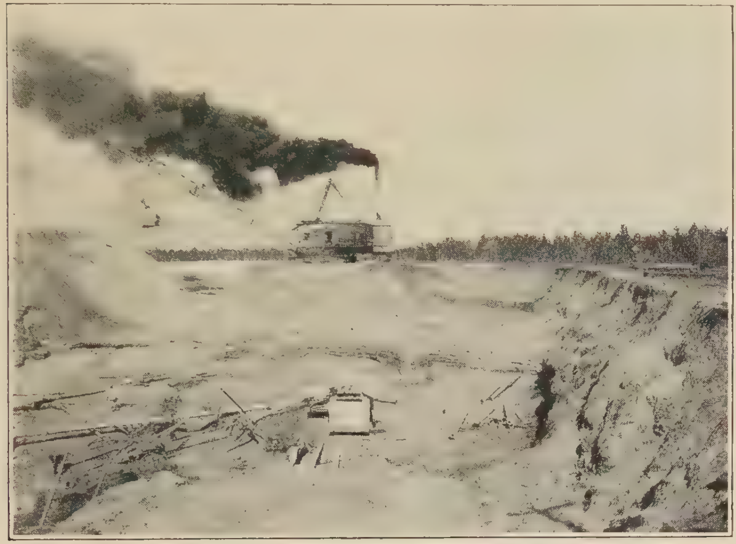

FIG. 257. Surface mining of phosphate rock in Florida

In general, the service of geology in the exploitation of the nonmetallic mineral resources is (1) to aid in the discovery of valuable materials, (2) to estimate the amount of material in any given deposit from a study of its geologic relations, (3) to determine the grade and therefore the commercial value of a deposit, and (4) to contribute to the solution of the structural problems which in many cases complicate and greatly increase the cost of extraction.

Geology and engineering. The rocks of the lithosphere are the major seat of human activities. In them man lays the foundations for his houses, digs his tunnels, sewers, aqueducts, and subways, and on them he constructs his roads. The rivers of the lands are the chief arteries of transportation and are an important source of power. In countless ways the activities of man put him in contact with problems of a geological nature, and with the progress of time the geologist is more and more becoming the associate of the engineer.

One of the most important services of geology to engineering construction is the ability to estimate the amount of water likely to be encountered in mining operations, in excavating tunnels, and in laying foundations for buildings. In the erection of great dams the geologist can give important advice regarding the strength of the underlying rocks to support the structure and their ability to prevent leakage. Strength of rock is also an important factor in determining the type of foundation for buildings and in choosing proper sites for railroad and wagon-road beds. Knowledge of wave force, tides, and currents is important in the construction of breakwaters, lighthouses, and all other structures near the ocean. In practically every structure raised by man on the surface of the earth, problems are encountered which can best be solved through the application of geological principles.

GEOLOGY AND THE LARGER AFFAIRS OF MAN

Geology and law. With the progress of the discovery and development of the mineral resources of the world there has come a large growth in mining law relating mainly to the ownership, leasing, and extraction of mineral deposits. In many cases the science of geology is called upon not only in the framing but also in the interpretation of such laws. In addition to mining laws, there are laws pertaining to duties on valuable minerals, laws that relate to the use of coast lines and rivers, laws that pertain to water rights in irrigation projects, and many others that involve geological principles.

Both Federal and state geological surveys have made extensive researches into the geology and mineral resources of public lands newly opened to development. Such researches form the basis for laws pertaining to the leasing of such lands.

Much litigation has arisen over the Federal mining law which gives the owner of the "apex" of a valuable mineral vein the right to follow that vein down the dip, even if it takes him beyond the marginal vertical planes passed through surface boundaries of his property into places below the surface property of others. This law is easily interpreted in regard to a simple lode with a single clean-cut outcrop which is clearly the top, or apex. Most mineralized veins, however, are not simple. Many of them branch and have more than one apex; many others are so irregular and poorly defined that it is exceedingly difficult to ascertain which claim has the extralateral rights. In many cases thoroughgoing geological surveys must be made for purposes of litigation. Although many famous "apex" trials have taken place, the complexities of nature have thwarted all attempts to frame such a definition of the apex of an ore body as can be easily interpreted in all cases. While the law stands in its present form geologists will undoubtedly be called to court in "apex" cases in the future as they have been in the past. From the legal point of view the "apex" law is extremely unsatisfactory, but the law has greatly enriched the science of geology. Some of the best studies ever made of bodies of ore were done in connection with "apex" litigation.

Geologists have many times proved useful in interpreting terms in contracts which pertain to the earth. Such terms as *earth, dirt, rock,* and *hardpan* are open to various interpretations, and where sums of money are involved the difference in interpretation often leads to conflict. The geologist is then called in to settle the dispute by framing a definition of the rock material in a scientific manner.

The laws touching geological principles are too numerous to be all mentioned. The use of streams for placer mining, the damages to property due to mining operations on adjacent property, and many other situations have made certain laws necessary. Where the framing and interpretation of such laws require a sound knowledge of earth science, the service of competent geologist is indispensable.

Geology and conservation. The mining industry, unlike most others, is obviously running downhill, with the ultimate goal the exhaustion of the mineral resources of the earth. The farmer harvests a crop from his fields, knowing well that other crops will grow in the years to come. The miner takes his ore from the mine and knows that the mine is just that much poorer. In mining there is but one crop; when that is harvested, the mine becomes worthless. Nature has not been prodigal with her mineral treasures. She has hoarded them in relatively small quantities through long ages. Many centuries are needed for the formation of a seam of coal which can be exhausted in a few years. Some metals are even now becoming rare, and it is certain that the complete exhaustion of valuable oil pools is not far in the future.

Not only the gradual ruin of rich mineral deposits but the rapid acceleration in the demand for such materials make the matter of conservation one of pressing importance. Obviously the only way to conserve our diminishing mineral resources is to eliminate waste in mining and to devise more efficient use for these valuable materials. Here it is that the geologist meets with the engineer, the metallurgist, the mine-operator, the economist, and the consumer. All nations of the world are waking to the need of conserving their raw materials, their mineral resources above all. In the United States both public and private attempts are being made to conserve valuable minerals, especially fuels.

While such attempts will greatly extend the life of our mineral resources, there is no way to prevent the exhaustion of some valuable deposits. The mining of high-grade ores of some metals cannot extend beyond the inevitable time when all known high-grade ores of these metals are mined out. When that time comes, the mining industry will be forced to turn to the use of the low-grade ores, heretofore almost neglected. These ores are disseminated so widely through the rocks that they probably can never be exhausted. The utilization of low-grade ores is developing rapidly, so that today, under an increased efficiency in methods of extraction, many deposits are being mined profitably which could not have been mined two decades ago except with great financial loss. The evolution of the mining industry will be a gradual change from the mining of high-grade materials to the extraction of low-grade materials. With the continued improvement of mining methods, the economical use of the products after they leave the mine, and international coöperation, our mineral resources can be conserved almost indefinitely.

Military applications of geology. During the World War earth science found many new applications, both behind the lines and at the front. All contenders realized that success depended largely upon the availability of certain minerals without which war would be impossible. This led to the most careful scrutinizing and stock-taking of the mineral reserves of the entire earth, a task performed with the aid of geology. Better mining methods and more economical use were established for many mineral products of peculiar importance during war.

The war gave an impetus to the construction of topographic maps, for use in coast defense as well as on the actual field of battle. Some of the field maps, especially those of German authorship, were constructed with the utmost care as to detail, so that they must have been of great value to field officers in conducting their campaigns. Leith, in commenting on the German field map, says:[1]

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> Features represented on these maps included topography; the kinds of rocks and their distribution; their usefulness as road and cement materials; their adaptability for trench digging, and the kinds and shapes of trenches possible in the different rocks; the manner in which material thrown out in trenching would lie under weathering; the ground-water conditions, and particularly the depth below the surface of the water table at different times of the year and in different rocks and soils; the relation of the ground-water to possibilities of trench digging; water supplies for drinking purposes; the behavior of the rocks under explosives, and the resistance of the

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[1] C. K. Leith, The Economic Aspects of Geology, p. 408. Henry Holt and Company, 1923.

ground to shell-penetration; the underground geological conditions bearing on tunneling and underground mines; and the electrical conductivity of rocks of different types, presumably in connection with sound-detection devices and groundings of electric circuits.

War, more than any other agency, showed the great variety of detailed applications for earth science. These were largely in connection with field operations, the location of water supply, and, to a lesser degree, the building of roads. In a larger sense the war proved the real importance of mineral resources and demonstrated clearly the international character of the problem of their exploitation and utilization.

The educative value of geology. It would indeed be an oversight not to speak of that phase of service which geology renders to those who study it as a part of their school or college course. Nothing is better calculated to stimulate the imagination of the student, to enhance his enjoyment out-of-doors, to increase his appreciation for nature, to broaden his conception of time, and to sharpen the rational faculty of his mind.

W. M. Davis, in an admirable essay on "The Disciplinary Value of Geography," summarizes the different mental processes involved in an attempt to solve a geographical problem. Since the steps are identical in the pursuance of a geological investigation, we may recount briefly the points established by this great logician of the earth sciences.

It is obvious that the first step toward the solution of a geological problem is the acquisition of certain facts. The student gathers the facts involved in the problem either through original outdoor investigation or by accepting the facts observed by others and recorded in books and maps. Great discrimination must be exercised in either case to avoid what appears true but what is really false. These facts should be recorded in simple empirical terms based entirely on what is seen and not on that which might be inferred to be seen. Many terms, such as *delta, flood plain, volcano, cirque,* and others descriptive of geological phenomena, involve a certain amount of theory and should be used with care in making the first statement of the facts of a problem.

As the gathering and recording of facts go on, certain similarities and dissimilarities are observed between newly gained facts and those acquired through previous experience. The facts tend to group themselves in regard to certain features. The second step in the progress of investigation is to make provisional generalizations about groups of similar facts.

After the investigation has proceeded from the recognition of separate facts to the induction of generalizations, the third step is a search for theoretical explanation. An enterprising student cannot long pursue the inductive process of reasoning without seeking the cause for his generalizations. At this point the problem offers great opportunity for the exercise of the inventive faculties, and the student who lacks such faculties can go no farther with a geological investigation.

When a working hypothesis which seems to satisfy certain facts has been invented, it must be scrutinized critically. The investigator must look for further hypotheses in case the first should prove faulty or inadequate in the light of more facts. Before the value of any hypothesis can be recognized, a deduction of the consequences must be made. Here comes in the use of an entirely new faculty of the mind, the power of deduction.

After establishing just what would happen in consequence of any hypothesis, these consequences must be compared with the facts from which the hypothesis did *not* take origin. In this way a preliminary judgment as to the truth of any given hypothesis may be made.

When all these steps have been faithfully carried out, the student must go over his entire work and revise it wherever necessary. He must look for facts which may be of doubtful value; he must search for neglected facts which may have an important bearing on the problem; above all, he must see if at any point he has compromised his intellectual honesty in accepting imperfections or in forcing or selecting the facts to fit a favorite hypothesis. Only after all this has been done can a final judgment be made.

In a brief outline of the subject matter of geology it is apparent that the steps in the acquisition of the knowledge presented cannot all be traced. The author of this book has attempted to bridge the gaps between cause and effect regarding the phenomena discussed, as far as space permits. The alert student will find many occasions to ask the questions "why" and "how." It is here that the teacher must supplement the text in showing the paths through inference and deduction at the ends of which the answer may in many cases be found.

While not many are stimulated in a first course in geology to use the subject matter of the science to develop the rational faculties of the mind, all can, in the words of John Burroughs, "add to the resources of their lives." Scenery will take on a new meaning; time will no longer be viewed in the light of man-written history; the earth will become more than a mere abode. These cultural attributes of geology constitute, perhaps, the greatest educative value for the greatest number of students, and it is to the development of these that this book is largely devoted.

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